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Sustainability of the agri-food system's characterization with food sovereignty framework and the evaluation approach of the major threats

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Sustainability of the Agri-food System's Characterization with Food Sovereignty Framework and the Evaluation Approach of the Major Threats.

Caracterización de la Sostenibilidad del Sistema Agroalimentario en el Marco de la Soberanía Alimentaria y Aproximación a la Evaluación de sus Principales Amenazas.

Caracterització de la Sostenibilitat del Sistema Agroalimentari en el Marc de la Sobirania Alimentària i Aproximació a l'Avaluació de les seves principals Amenaces.

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General Introduction

In 2015 the United Nations (UN) approved the Sustainable Development Goals (SDGs) consisting of 17 goals, composed of 169 targets that should be covered by the year 2030 – (see Box 1 below). Each SDG focuses on a specific issue, but as a whole, they include a systemic view bases on the six dimensions presented in an article published by Kates et al. (2005) people, economy, society to be developed, natures, life support, and community.

The SDGs followed the Millennium Development Goals (MDGs), which consisted of eight objectives aimed at addressing the world's poorest needs, and that the United Nations Organization (UN) set in 2000 to be reached by 2015. The first MDG required to eradicate extreme poverty[1] and hunger; such goal was broken down into three different targets:

I. To halve between 1990 and 2015, the proportion of people whose income is less than one US dollar a day.
II. To achieve full and productive employment and decent work for all, including women and young people.
III. To halve between 1990 and 2015 the proportion of people who suffer from hunger.

The first target was reached five years ahead of 2015, according to the MDGs webpage. On the contrary, the second and the third were not achieve. By 2015 300 million workers were living below de 1.25 USD poverty line, and the proportion of young women and men employed decrease from 5% in 1991 to 4% in 2015. Regarding the third target, the portion of undernourished people decreased from 23.3% between 1990-1992 to 12.6 % between 2014-2016 (UN, 2015).

Despite not reaching the target for 2015, the downward trend was maintained for many years. However, from 2015 to date, such a descending trend has not held. The percentage of people undernourished has been kept at similar levels since then; and, in 2019, the trend reversed, showing an increment in the number of undernourished people of around 690 million (Figure 1); this, even though the world already produces enough food to feed more than the whole current population (Berners-Lee et al., 2018; Holt-Giménez et al., 2012). More concerning is the idea that this tendency is expected to change far from diminishing due to the current COVID-19 worldwide health contingency. The UN Food and Agriculture Organization (FAO) has estimated an additional 83 to 132

[1] Poverty understood as the proportion of people whose income is less than 1.25 USD equivalent per day.

million people undernourished in 2020 due to the pandemics and the associated socio-economic crisis (FAO, 2020).

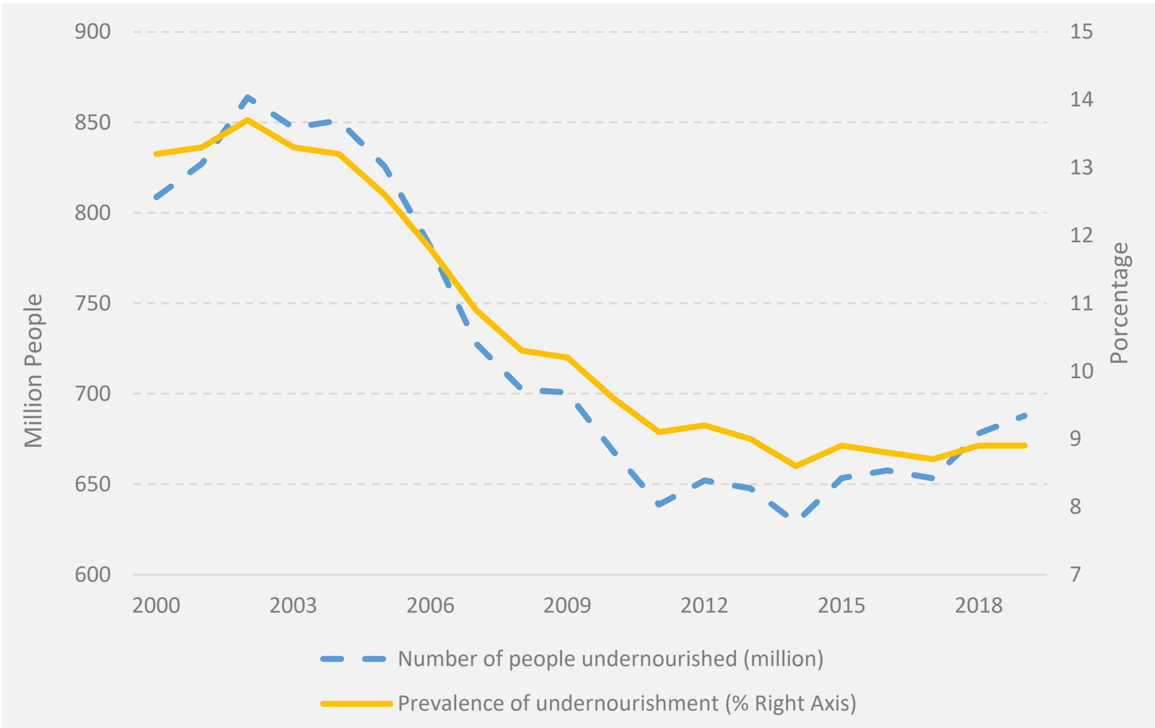

Figure 1 - People undernourished from 2000 to 2019
Source: FAOSTAT

Derived from the transition to SDGs, the new goal recognizes that a broader approach is needed to end hunger since the SDG2 links the objectives of zero hunger, food security, and improved nutrition to promote sustainable agriculture (Box 1).

SDG2 is the goal dedicated to reaching zero hunger by 2030. Nevertheless, what does hunger means? Hunger is not an easy concept to define since it may include emotional and personal-physical sensations (Cannon & Washburn, 1912); thus, it does not have a generally accepted definition. Caparrós (2014) presents the duality of the term hunger. On one side, there is nothing more familiar to us than hunger, as is expected that we feel it before a meal.

On the other side, to some people, the concept of hunger is away from their reality since they are not going to die from starvation, and, unfortunately, people suffering real hunger rarely have a voice in the UN. Yet, there is no war, civil conflict, nor plague that had killed more people than hunger (Our

World in Data, n.d.). Around 45% of deaths among children under five years old are linked to undernutrition (World Health Organization (WHO), n.d.) (Figure 2).

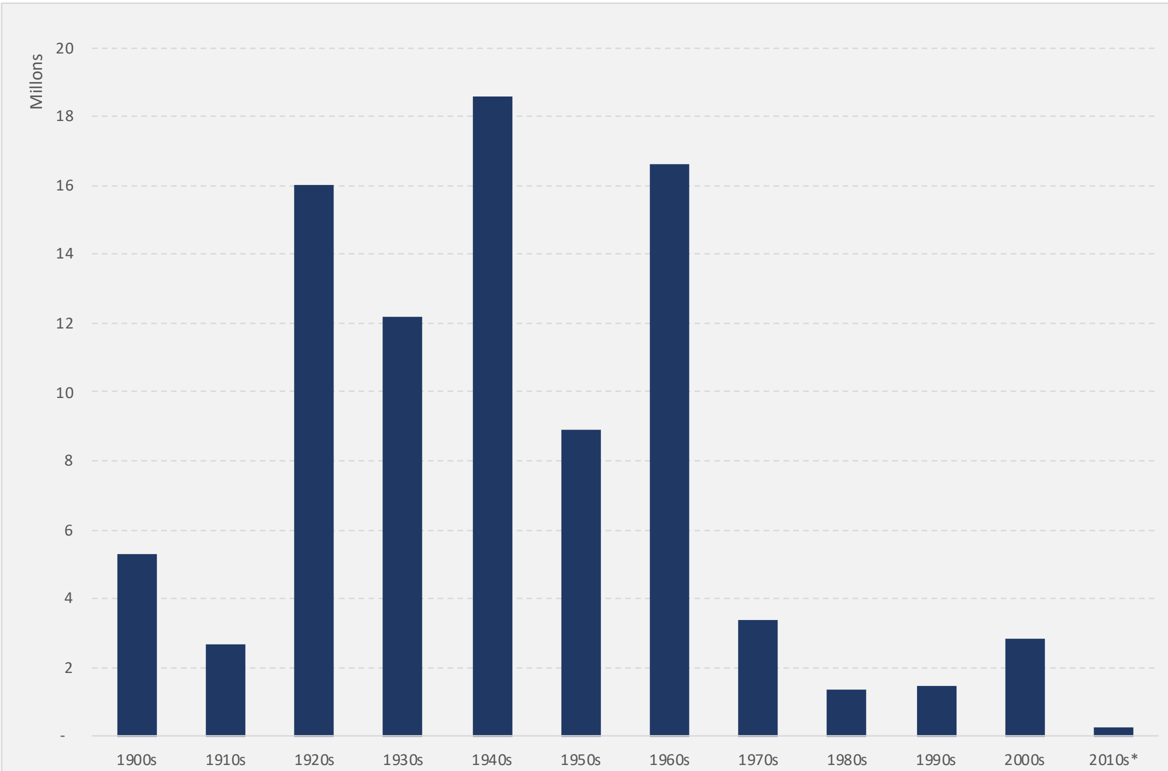

Figure 2 – Famine victims worldwide since the 1900s
Source: OurWorldinData.org with data as of 2016

Hunger and undernourishment are not the only problems that the current agri-food model faces. The UN is looking deeply into some specific threats that can severely constraint the world's possibilities to achieve the zero hunger goal: global environmental change, particularly climate shocks, social conflicts worldwide, the locust crisis, and the recent CoVID-19 impacts (UN, n.d.).

Environmental damage caused by agricultural activities is a constant threat, both for present needs and for the system's sustainability in time, particularly under the uncertain consequences of climate change. The planetary boundaries developed by Rockstrom et al. (2009) are very closely related to agriculture. They identified a limit of nine biophysical processes in Earth that, if surpassed, the life for humanity will be threatened. These processes are land use, climate change, biogeochemical flows, water use, biodiversity loss, ocean acidification (Figure 3).

2.1

By 2030, end hunger and ensure access by all people, particularly the poor and people in vulnerable situations, including infants, to safe, nutritious, and sufficient food all year round.

2.1.1. Prevalence of undernourishment

2.1.2. Prevalence of moderate or severe food insecurity in the population, based on the Food Insecurity Experience Scale (FIES)

2.2

By 2030, end all forms of malnutrition, including achieving, by 2025, the internationally agreed targets on stunting and wasting in children under five years of age, and address adolescent girls' nutritional needs, pregnant and lactating women, older persons.

2.2.1. Prevalence of stunting (height for age <- two standard deviations from the median of the World Health Organization (WHO) Child Growth Standards) among children under five years of age

2.2.2. Prevalence of malnutrition (weight for height >+2 or <- two standard deviations from the median of the WHO Child Growth Standards) among children under five years of age, by type (wasting and overweight)

2.3

By 2030, double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists, and fishers, including through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets and opportunities for value addition and non-farm employment.

2.3.1. Volume of production per labor unit by classes of farming/pastoral/forestry enterprise size

2.3.2. Average income of small-scale food producers, by sex and indigenous status

2.4

By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, which help maintain ecosystems, strengthen capacity for adaptation to climate change, extreme weather, drought, flooding, and other disasters, and that progressively improve land and soil quality.

2.4.1. Proportion of agricultural area under productive and sustainable agriculture

2.5

By 2020, maintain the genetic diversity of seeds, cultivated plants, and farmed and domesticated animals and their related wild species, including through soundly managed and diversified seed and plant banks at the national, regional, and international levels, and promote access to and fair and equitable sharing of benefits arising from the utilization of genetic resources and associated traditional knowledge, as internationally agreed.

2.5.1. Number of plant and animal genetic resources for food and agriculture secured in either medium or long-term conservation facilities

2.5.2. Proportion of local breeds classified as being at risk, not-at-risk, or the unknown level of risk of extinction

2.a

Increase investment, including through enhanced international cooperation, in rural infrastructure, agricultural research and extension services, technology development, and plant and livestock gene banks to enhance agricultural productive capacity in developing countries, in particular, least developed countries.

2.a.1. The agriculture orientation index for government expenditures

2.a.2. Total official flows (official development assistance plus other official flows) to agriculture

2.b

Correct and prevent trade restrictions and distortions in world agricultural markets, including through the parallel elimination of all forms of agricultural export subsidies and all export measures with equivalent effect, in accordance with the mandate of the Doha Development Round.

2.b.1. Producer Support Estimate

2.b.2. Agricultural export subsidies

2.c

Adopt measures to ensure the proper functioning of food commodity markets and their derivatives and facilitate timely access to market information, including food reserves, to help limit extreme food price volatility.

2.c.1. -indicator of food price anomalies

Box 1 – Targes for the Sustainable Development Goal Number 2 – End hunger, achieve food security and improved nutrition and promote sustainable agriculture.

Source: UN

Figure 3 – Planetary Boundaries

Source: J. Lokrantz/Azote based on Steffen et al. (2015)

Regarding land use, erosion, and land degradation, 2009 FAO (2009) reported that the intensive agricultural model[2] had caused almost 70 percent agricultural soil loss (Figure 4). Currently, about a quarter of the Earth's ice-free land area is subject to human-induced degradation, and soil erosion from agricultural fields is estimated to be currently 10 to 20 times (no-tillage) to more than 100 times (conventional tillage) higher than the soil formation rate (IPCC, 2020). Regarding changes in land use, it is estimated that 80 percent of new agricultural fields had been taken from tropical forests, leading

[2] The intensive agricultural model refers to that in which there exist an indiscriminate use of fertilizers and pesticides.

to deforestation and severely affecting the existing biodiversity and critical environmental ecosystems in the tropics (Foley et al., 2011).

The latest update on the Planetary Boundaries Research (Steffen et al., 2015) shows the alarming levels on the biogeochemical flows (potassium and nitrogenous cycles) due to primary agricultural activities are way far from the planet limits, despite that the researchers emphasize that the proposed boundaries may be larger for an optimal allocation of nitrogenous (N) and potassium (P) over the globe. In this regard, despite food production has increased by 240% since 1960, the use of N fertilizer has increased over 800% (IPCC, 2019)

Biogeochemical flows are perhaps the more noticeable impact that the intensive agricultural model is having in the Earth's ecosystems, but it is not the only one. Agriculture also affects freshwater consumption, since it represents 70% of globally usable water withdrawals, according to FAO's Global Information System on Water and Agriculture (AQUASTAT); climate change and land-system change, since it is a significant emitter of greenhouse gases (GHG) and user of land (Foley et al., 2011; Smith et al., 2014; West et al., 2014).

The loss of biodiversity is also related to agricultural practices, and at the same time, such loss directly affects food production. As The State of World's Biodiversity for Food and Agriculture has stated: "*biodiversity of food and agriculture (BFA) helps to make production systems and livelihood more resilient to shock and stresses, including those associated with climate change*" (FAO, 2019).

Another relevant boundary relates to climate change, probably one of the most emergency crises we are living in today. Agriculture, forestry, and land use (AFOLU) contribute to 23% of total greenhouse gases emissions (GHG), and the food system as a whole is estimated to have a contribution of 21-37% (Mbow et al., 2019).

Therefore, from the seven measured planet boundaries, the agri-food system is directly related to a least five of them. It encompasses a circular relationship since, on the one hand, the agri-food system is the main driver of these five boundaries, but on the other hand, it is also affected by them.

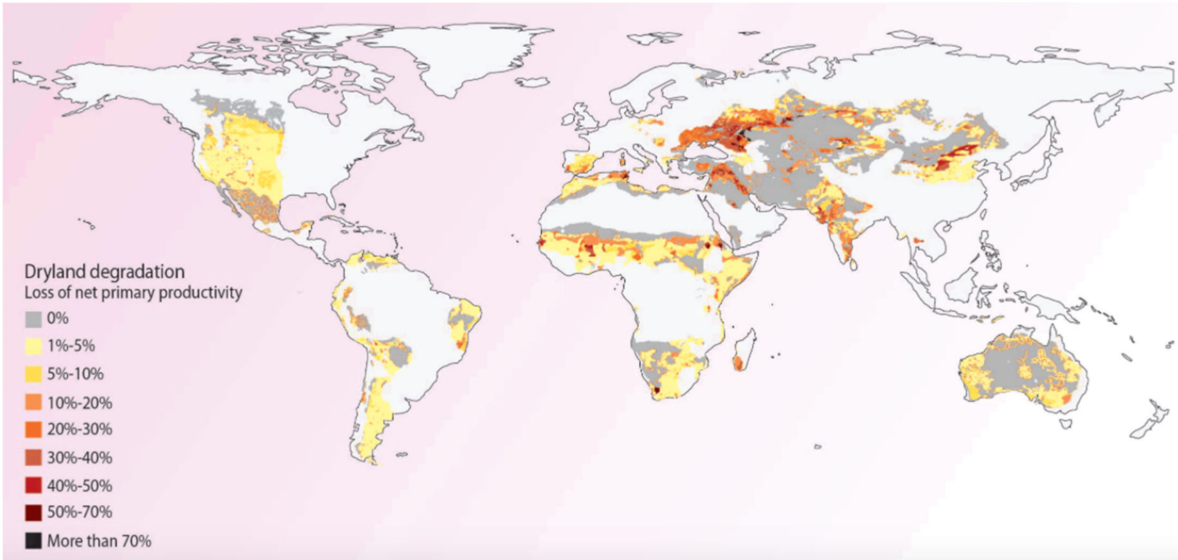

Figure 4 – Land degradation results in decreasing agricultural productivity
Source: (Zika & Erb, 2009)

Regardless of the stressful situation in which the soils find themselves, the global food production model has continued to bet on producing more, even though the problem remains on the unequal distribution of food and not on its scarcity (Collins & Chandrasekaran, 2012). The socio-political dimension around the global agri-food system also plays a vital role in its performance, just as the socio-ecological relations embedded in the agri-food systems do. To achieve SDG2, one should undertake an in-depth analysis of such relationships and understand their drivers and consequences. The agri-food system needs to be understood, analyzed and managed as a complex socio-ecological system (Ericksen, 2008; Mbow et al., 2019; Rivera-Ferre, 2012).

From an anthropocentric point of view, the main objective of the agri-food systems must be to attain food security for its population (Ericksen, 2008). This is to say that the system must ensure that "*every person, at all times, have physical, social and economic access to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life*" (World Food Summit, 1996).[3] However, this must be done without harnessing the environment, as I have presented above the close connections between food and environmental degradation production. All the evidence gathered in the last decades regarding food systems have recently landed in need to

[3] http://www.fao.org/organicag/oa-specialfeatures/oa-foodsecurity/en/

transform current food systems to build sustainable food systems. However, there are different forms to build these food systems, which depend on the way food is framed (SAPEA, 2020).

SAPEA (2020) highlights three main framings: food as a commodity, food as a human right, and food as a common good. Food as a commodity is usually the most used policy framing. This carries out a conceptual problem from the origin, since such framing links food to global market needs rather than by the local populations' necessities, hence increasing the risks for the proper fulfillment of the original agri-food system goal. Alongside this conceptual framing of food as a commodity, also stand out the use of food as an input for the production of energy (agrofuels[4]), the feeding of cattle, and the generation of economic wealth through both regulated and unregulated (price speculation) food markets. This perspective offers a plausible explanation of why in the world where food is produced in abundance where the Gross Production Index Number for Food has continuously grown over the past decades (Figure 5), hunger and undernourishment still affect one every nine people worldwide every year.

[4] Biofuels are fuels derived from biomass like wood, plants and manure, which have been used historically for producing heat, light and electricity among other necessities. Agrofuels, particularly, are biofuels coming from agricultural products like bioethanol or biodiesel, these fuels are now the center of two major debates: the first relates to the ethical question on whether food, which could well shovel the problem of hunger in the world, should be used to produce energy. The second refers to whether energy generation by means of biofuels is indeed more sustainable and resource efficient than alternative sources of energy. Many authors have analyze this (Giampietro & Pimentel, 1993; Patrick, 2011; Pimentel, 2008; Raman & Mohr, 2014)

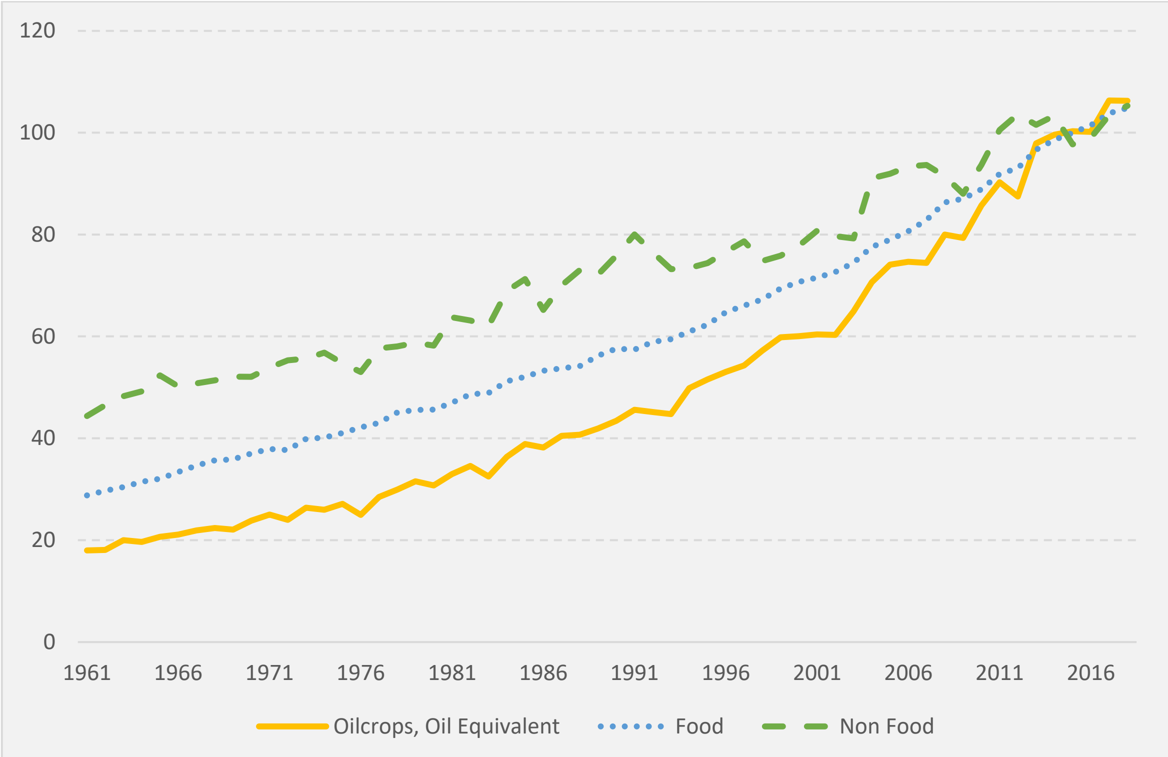

Figure 5 – Gross Production Index Number (2014-2016 = 100)
Source: FAOSTAT

Governmental bodies, as well as private firms, have tackled this problem by increasing investments to produce more food and to promote a wider opening of food markets, given their expectancy that despite the external constraints (i.e., climate change) and population growth rate, there would remain decades of inexpensive food production (IPCC, 2007; Soussana, 2014). However, empirical evidence suggests that in time these measures have aggravated the problem rather than mitigated it. In the last years, historical levels of undernourishment and the loss of natural resources have been reached.

Food as a human right framework considers people's right to access adequate food daily as a part of the right to an adequate living standard. Article 25.1 of the Universal Declaration of Human Rights recognized it in 1948, and The International Covenant on Economic, Social and Cultural Rights in 1966. Although the right of food was recognized by international institutions many years ago, there is still a not clear path to enforce its completion, as it lies in the government level field of actions, and its accomplishment integrates a broader scope of dimensions linked with other fundamental human rights. Anderson (2008) introduced the concept of rights-based agri-food systems and provided a six criteria framework as a base for their development:

1. The first criteria consider the absence of human exploitation and absolute respect for every human right.
2. The second empathize with the need for democratic participation in agri-food system choices that impact all the system's stakeholders.
3. The third is to guarantee fair and transparent access to food production resources, including knowledge sharing.
4. The fourth is to have multiple independent buyers and access to [local] markets.
5. The fifth is o guarantee the absence of resource exploitation.
6. Finally, the sixth mentioned that the system should not allow any impingement on people's ability in other locales to meet these criteria (e.g., through trade relationships that undermine decent wages, fair prices, environmental quality, and transparency of access to information in other countries).

The High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security (HLPE, 2020) recognized the "*urgent need for strengthening and consolidating conceptual thinking around food security and nutrition to prioritize the right of food*" by articulating an international legal framework for the right to food which comprises the growing local efforts done so far to achieve the full realization of this fundamental human right. They call for a transformation of the global narrative towards food as a human right.

Approaching food as a human right provides the basis for different food system framings such as food sovereignty (Claeys, 2015; Wittman, 2011) or food as commons (Rundgren, 2016). It also provides a moral basis for the idea of 'good food,' understood in terms of access to healthy, nutritious food and the lively cultural values associated with food, such as identity, taste, and pleasure.

Finally, food framed as a common good puts sustainability at the center of the discussion since it enhances the value of food accessibility rather than that of food production. This framework pushes for the study of sustainability's social and environmental dimensions to identify the structures, including governmental, public, and private sector institutions, required to facilitate food access. This notion also considers a cultural dimension based on territorial diversity in soils, climate, ecosystems, farming styles, and food cultures that shape diversity worldwide (SAPEA, 2020).

There is an ongoing debate in the agri-food system between those who want to strengthen what McMichael (2009) characterizes as the corporate food regime[5] and propose alternative production routes linked to food's three conceptual framings. The former group is constituted by governmental bodies, global institutions, monopolies of the agri-food industry, universities, think tanks, and philanthropic organizations that proposed a so-called "green revolution"[6] as a solution to hunger and rural poverty. Their strategy is centered on producing more food to achieve food security, for which they incentivize the use of biotechnology and genetically modified organisms (GMOs) and greater exposure to global markets (Holt-Giménez & Altieri, 2012).

Conversely, the latter group is integrated by specific social, civil organizations (SCOs), farmers groups, and non-governmental organizations (NGOs), which propose local perspective alternatives. This means to focus production for farmers that are aimed at the sustainability of the agri-food system itself. Some of these alternatives are intended to change the existing paradigm and return to the traditional roots of farming and agricultural production by putting [small] farmers in the center of the conversation recognizing their essential role within the system.

Objectives

The three frameworks exposed above are further analyzed in different stages of this work, as it is the **main objective** of this work to adapt and establish key parameters that allow characterizing the degree of sustainability of the global agri-food system following alternative framings of food, through the study and analysis of its agents, interactions, main strengths, and vulnerabilities. Mainly, I focus

[5] "A food regime is a temporally specific dynamic in the global political economy of food. It is characterized by particular institutional structures, norms, and unwritten rules around agriculture and food that are geographically and historically specific" (Otero et al., 2013). McMichael name the current dominant production and consumption structure at global scale as de corporate food regime (Holt-Giménez & Altieri, 2012; McMichael, 2006). The corporate food regime is "a relatively stable set of relationships privileging corporate agriculture, in the service of capital accumulation on a world scale and at the expense of smallholder agriculture, local ecologies and 'redundant' urban fringe-dwellers" (McMichael, 2009).

[6] The term Green Revolution refers to the international movement promoted in by the mid of XX century, that incorporates changes to the traditional agricultural model with the aim of increasing agricultural production. Such changes are focused on the mass use of fertilizers, pesticides and herbicides, genetic modification, implementation of artificial irrigation systems that allow intensive exploitation of soil, and the production at large scale of a single crop.

on food as a human right to provide an alternative framework of the agri-food system's sustainability as food sovereignty (Claeys, 2015; Wittman, 2011). Following Jabareen's (2009) methodology, I aim to develop food sovereignty as a conceptual framework to achieve sustainable food systems.

The following **secondary objectives** will allow reaching the principal objective:

i) To propose a methodological analysis that incorporates and reviews previous methodologies (Ruiz-Almeida & Rivera-Ferre, 2019).

ii) To propose a conceptual analysis of the main alternatives that foster the agri-food system's sustainability (Ruiz-Almeida, Rivera-Ferre, and Rosas-Casals, forthcoming), and

iii) To validate the food sovereignty framework by creating a new concept, food debt (Oteros-Rozas & Ruiz-Almeida et al., 2019).

This dissertation is structured as follows; the next chapter presents the database. Using food sovereignty as a conceptual framework, we propose a quantitative methodology that analyzes food systems' functioning at the international level. We present a database with 97 indicators distributed into six categories: 1) access to resources; 2) productive models; 3) commercialization; 4) food consumption and the right to food; 5) agrarian policies and civil society organization; and 6) gender. We also present the limitations found in developing the database and its potential applications for a wide variety of factors. This work derives from a publication on Food Security (Ruiz-Almeida & Rivera-Ferre, 2019), but previous to its publication, this work was presented in the 3rd International Conference on Global Food Security, which took place in Cape Town, South Africa in December 2017; and in the VII International Agroecology Congress, held on Cordoba, Spain in June 2018. Besides, it contributes to the IPBES regional assessment report on biodiversity and ecosystem services for Europe and Central Asia (IPBES, 2018), where I am recognized as a contributing author.

In chapter two advances the concept of food sovereignty as a conceptual framework to analyze agri-food systems' sustainability following the steps proposed by Jabareen (2009) to build conceptual frameworks. In that work, we integrate similar concepts following the four agrarian questions (agriculture, quality, environmental, emancipatory) and the three fundamental outcomes of sustainable agri-food systems: food and nutrition security, environmental resilience, and social well-being.

In chapter three, I use the database for analyzing the global agri-food system using a socio-ecological approach. In a collaborative work among researchers from the University of Vic and Autonomous University of Madrid, we conducted a quantitative multivariate assessment of 43 indicators of food sovereignty and 39 indicators of socio-demographic and social well-being and environmental sustainability in 150 countries; we depict the global food panorama. The results indicate an agri-food debt, i.e., disequilibria in the natural resources consumed, the environmental impacts produced, and the social well-being attained by populations in regions that play different roles within the globalized agri-food system. This work was derived in a publication in the Proceedings of the National Academy of Sciences of the United States of America, PNAS (Oteros-Rozas & Ruiz-Almeida et al., 2019).

Finally, I conclude this dissertation with final remarks and further work on the forthcoming final paper to be submitted in the first quarter of 2021 to the Special Issue of the journal sustainability entitled "Sustainable agri-food systems: environment, economy, society, and policy."[7]

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[7] Further information on this special issue on:

https://www.mdpi.com/journal/sustainability/special_issues/agri-food_systems

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Chapter 1. Internationally-based indicators to measure Agri-food systems sustainability using food sovereignty as a conceptual framework

Abstract

Agri-food systems are essential in achieving food security and achieving both social and environmental sustainability. Although different actors use different frameworks to define and assess food systems sustainability, there is a growing consensus on approaching them from a complex socio-ecological systems perspective. However, existing frameworks often lack the political dimension in the analysis of food systems outcomes. Food sovereignty has emerged as a proposal that centers the discussion in the entire system, emphasizing food's political aspects. In this paper, using food sovereignty as a conceptual framework, we propose a quantitative methodology that allows analysis of food systems' functioning at the international level. We present a database with 97 indicators distributed into six categories: 1) access to resources; 2) productive models; 3) commercialization; 4) food consumption and the right to food; 5) agrarian policies and civil society organization; and 6) gender. We also present the limitations found in developing the database as well as its potential applications for a wide variety of factors.

1 Introduction

Agri-food systems, through their multiple interactions with global environmental change, play a significant role in human well-being (Ericksen, 2008). They are essential not only in achieving food security but also in achieving both social and environmental sustainability. For instance, issues such as land-grabbing, biodiversity depletion, soil degradation, water contamination, use of unsustainable energy sources, habitat loss, global health, or poverty are all related to agri-food systems (McIntyre et al., 2009). They are both greenhouse gas emitters (Smith et al., 2014) and one of the coupled nature-human systems more vulnerable to climate change (Porter et al., 2014). Yet, it is acknowledged that nowadays, agri-food systems do not fulfill their primary objective of providing healthy and nutritious food to people without harnessing the environment. Thus, designing policies to promote actions towards the sustainability of agri-food systems is imperative. However, designing these policies is a complicated task given i) the relevant social, ecological, and economic impacts they may have, ii) the multidimensional consequences of the decisions taken, and iii) the absence of a standard and agreed definition of what is a sustainable agri-food system. Indeed, different actors (e.g., retailers, governments, producers, civil society organizations) define sustainable agri-food systems in different ways e.g. depending on the starting point of their analysis (Allen, 2013; Eakin et al., 2017) and their narratives and scales (Rivera-Ferre, Ortega-Cerdà, et al., 2013; Thompson et al., 2007). Indeed, food security has been defined as a wicked problem, where new governance arrangements have a key role to play (Breeman et al., 2015; Candel, 2014).

In principle, it could be stated that policies for sustainable agri-food systems, which rely on eco-social principles, should attend to the present needs and challenges regarding the production and provision of safe and nutritious food without compromising the ability of future generations to meet their own needs. The question is, how to achieve this goal? Despite the lack of consensus in defining a sustainable agri-food system, eradicating hunger is one core objective of international policies aiming to contribute to global sustainability, such as the Sustainable Development Goals (SDGs). In this regard, international food policies have since the early 1970s centered on achieving food security as the principal outcome of agri-food systems. However, despite several policy efforts since then, today, there are still 815 million people suffering from hunger (FAO, 2017a), and the objective to reach the zero hunger SDG2 for 2030 does not seem achievable. The evidence points that the current system appears to be productive in terms of agricultural yields (De Ponti et al., 2012; Ponisio et al., 2014) and that the world produces food for human consumption in abundance (Gustavsson & Cederberg, 2011), but it fails to be inclusive and to distribute the benefits to the poor equitably and the hungered while creating problems of overweight and obesity to more than 2 billion people in the world (WHO, 2018). In time, food security has evolved to stand as a concept that seeks to address concerns related to nourishment and public health (Maxwell, 1996). However, when intended as a unique outcome of agri-food systems, food security often fails to contemplate alternative dimensions of sustainability, such as environmental and social ones. The recurrent events of food crises, malnutrition, and famine worldwide, together with the environmental impacts linked to agri-food systems, have evidenced the failure of current food policies focused exclusively on a narrow definition of food security.

The problems related to food insecurity faced in the last decades have forced a paradigm change to include different social and environmental variables as fundamental to reach food security (Devereux, 2000; Patel, 2009). Some authors have proposed systemic approaches to study and manage agri-food systems in their objective to achieve food and nutrition security while considering both social and environmental aspects. Erickssen (2008) stated the relevance of analyzing *"the food system's interactions with global environmental change and evaluating the major societal outcomes affected by these interactions: food security, ecosystem services, and social welfare."* This approach includes the social and environmental components as fundamental drivers that affect the potential outcomes (food security), yet only from a technical perspective. Another interesting approach is climate-smart food systems (Wheeler & von Braun, 2013) that proposes a systemic approach to the "climate-smart agriculture" concept first launched by the Food and Agriculture Organization (FAO) in 2010. The proposal is centered on developing agri-food systems that are more resilient to climate change, impacting food, and nutrition security. This concept skips the political dimension of food systems and only addresses the environmental component of those elements linked to climate change. A more political approach was proposed by Fullbrook (2010), who stated the need to address food as security, which, according to him, would have positive consequences both to food security, poverty, and the environment. Several authors have suggested developing policies to favor sustainable agri-food systems; different frameworks are needed (McKenzie & Williams, 2015; Rivera-Ferre, Pereira, et al., 2013). This hard task requires a paradigm shift that replaces the traditional thought patterns in agriculture with a new concept that simultaneously addresses the key features of complex agri-food systems, including its strong social and political component.

During the Thirty-Second Regional Conference for Latin America and the Caribbean (Buenos Aires, March 2012), the FAO agreed to initiate discussions about alternative approaches to address hunger and the unsustainability of food systems. One such approach was food sovereignty (Nicastro, 2012). Food sovereignty was identified as a political concept that centers the discussion in the agri-food system, suggesting that hunger is the result of the concentration of the means of production in a few hands with the consequential exclusion of small producers, due to the worldwide generalization of the corporate food regime based on industrialized systems and export-oriented agriculture (McMichael, 2005) and the disenfranchisement of producers and consumers in the context of consolidated global food supply chains (Macdonald, 2007). This concept conceptualizes food as a human right, including its environmental and social aspects, which are viewed as drivers and outcomes of food security. More interestingly, this concept focuses on small farmers who, according to the proposal, have a central role to play. FAO's "State of Food and Agriculture" report (FAO, 2017a) shows that "85 percent of the world's farms are smaller than 2 hectares" (p.54). In this sense, Samberg et al. (2016) found that small farmers are crucial both in local and global food security despite excluded from mainstream policies. They support the livelihood of many of the most marginalized populations. Still, they also produce more than 70% of the food calories produced in Latin America, sub-Saharan Africa, and Southeast Asia using only 30% of the agricultural land. Farmers in these densely populated regions are responsible for more than half of the food calories produced globally, and more than half of several major food crops' global production.

The food sovereignty proposal addresses food systems from a holistic perspective that encompasses environmental, social, and economic aspects to find a political answer that guides the system towards sustainability. From this perspective, sustainable agri-food systems are defined as systems capable of ensuring all people's food security by making political efforts to address the root causes of hunger and malnutrition while preserving the environment, putting at the center of policies those people who produce food. This understanding of what a sustainable agri-food system is has a significant challenge: the need to measure whether different approaches at the country level give or not result in terms of food sovereignty and its expected outcomes (e.g., right to food, environmental sustainability, social justice). Other proposals of sustainable agri-food systems have their own metrics based on quantitative indicators. Still, food sovereignty has not, making it very difficult to elucidate whether the proposal is capable of achieving its objectives or not. There have been initial efforts to put forth a quantitative methodology that allows interested parties to measure and compare progress in this line (Ortega-Cerdà & Rivera-Ferre, 2010). However, there is still no existing framework that serves as a benchmark for comparisons among countries. The present paper attempts to fill in this gap by setting up a revised collection of international country-based food sovereignty indicators. Our objective is to operate as a benchmark to assess, in a standardized manner, the sustainability of agri-food systems across countries through the lens of food sovereignty.

This paper is organized as follows. In the following section, we describe the food sovereignty proposal and the initial efforts towards its measurement. Team two puts forth the methodology to define the categories that integrate the country level's food sovereignty framework to select and organize the indicators. Section three offers the resulting collection of indicators. In the last two quarters, we discuss the results, present some potential applications of the database, and the conclusions.

2 The food sovereignty proposal

In April 1996, the international peasant movement organization La Via Campesina[8] (LVC) developed the concept of food sovereignty, considering it a prerequisite to achieving genuine food security. Since its inception, the food sovereignty proposal has pursued to develop "just and sustainable agri-food systems" (Rivera-Ferre, 2008). According to this broad proposal, a sustainable agri-food system should aim at reducing poverty, promoting the development of rural areas and the sustainability of the environment from the perspective of social justice and gender equity (Desmarais, 2003; Holt-Giménez & Altieri, 2012; Patel, 2009; Rosset, 2011).

The most commonly used definition of food sovereignty is the one that emerged from the Declaration of Nyéléni, the first Global Forum on Food Sovereignty, celebrated in Mali (February 2007) which states that:

> *"Food sovereignty is the right of peoples to healthy and culturally appropriate food produced through ecologically sound and sustainable methods, and their right to define their own food and agriculture systems. It puts the aspirations and needs of those who produce, distribute, and consume food at the heart of food systems (…). It defends the interests and inclusion of the next generation. (…) Food sovereignty prioritizes local and national economies and markets and empowers peasant and family farmer-driven agriculture, artisanal fishing, pastoralist-led grazing, and food production, distribution, and consumption based on environmental, social and economic sustainability."*

Food sovereignty as a concept always refers to the right to food, which recognizes that people worldwide must have access to safe, nutritious, and culturally appropriate food and the necessary resources and mechanisms for its production and consumption to support themselves and their societies. This last definition shows the shifting from an agrarian to a food system focus. Food sovereignty currently adopts a systemic approach that also contemplates the environmental sustainability of production and consumption methods (Dekeyser et al., 2018). Today, food sovereignty is conceived by their supporters as a genuine precondition of food security (Patel, 2009)

[8] La Via Campesina is an international movement that emerges in 1993 from the union of millions of farmers, small producers, indigenous people and migrant workers. Currently it encompasses 164 local and national organizations in 73 different countries representing around 200 million peasants worldwide.

The food sovereignty proposal has managed to stand itself as a potential alternative to the current development model in the production, distribution, and consumption of food (Wittman, 2011). Different Civil Society Organizations (CSOs), Non-Governmental Organizations (NGOs), multilateral institutions (UNEP, Commissioner of the Right to Food, FAO) and Governments (Mali, Nepal, Indonesia, Ecuador, Bolivia) have acknowledged its potential in the development of sustainable agri-food systems.

Food sovereignty measurement

As the food sovereignty proposal has strengthened over the years, it has increasingly been the target of several studies and critiques (Dekeyser et al., 2018). At a theoretical level, many scholars agreed on its potential to reduce hunger and rural poverty (Altieri, 2009; Wittman, 2011), to pursue sustainable development in rural areas (Rosset, 2009, 2011), and to promote gender equity (Desmarais, 2003). Other authors raise influential critics to the proposal as it fails to be clear in how to connect the individual activities of small farmers with the growing needs of a dynamic and changing population (Agarwal, 2014; Bernstein, 2014), even suggesting that it could be better achieved with top-down policies.

Despite all these studies, only a few have aimed at developing analytical tools for measuring the outcomes of the proposal at different spatial scales (Binimelis et al., 2014). Thus, there is still a need for an accepted international framework on which individuals and organizations can measure the outcomes of different policies and actions in terms of food sovereignty, allowing comparisons at various spatial and temporal scales.

A highly accepted tool to measure outcomes of policies and ecosystems' performance is indicators since they simplify complex situations in a useful manner (Jackson et al., 2000). Developing indicators have become central to the debate on sustainable development, with many national and international organizations and academic institutions conducting significant research in the field (Gasparatos et al., 2008). As a general rule, the elaboration or selection of a set of indicators to measure specific actions' progress in a time frame requires first the establishment of the goals and objectives. Niemeijer & de Groot (2008) stated that making explicit the selection process and the framework used is essential in any process of indicators development since this determines which indicators are considered and clarifies the conclusions of the analyses based on them. In assessing agri-food systems from a food sovereignty perspective, the food sovereignty proposal is given the framework. It needs to rely on indicators that assess whether the outcomes are acceptable and in line with fulfilling the intended goals and objectives. Particularly, food sovereignty measurements must determine whether the proposal stands as a valid alternative to the current agri-food development model, for which no integrated and accurate data exist.

Defining the scale of analysis is also an essential step in defining the indicators. Since the analytical framework to develop the indicators is in all cases given by the goals and objectives of the food sovereignty proposal, categories and subcategories for allocating the indicators are similar regardless of the scale (Binimelis et al., 2014). Yet defining the scale is important because the sources of indicators and their objectives change depending on the context and the scale of analysis (global vs. local). At the local level, Badal et al. (2010) developed a set of indicators to measure the level and evolution of food sovereignty in Catalonia through participatory processes in the region. Vallejo-Rojas et al. (2015), through the integration of socioecological systems and vulnerability frameworks, developed their own set of indicators to measure outcomes of food sovereignty policies in local agri-food systems in the Ecuadorian Andes. Islam and Berkes (2016) integrated the food sovereignty approach with Sen's entitlement to analyze indigenous' people food security in Northern Canada

At the international level, Woodley et al. (2009) contributed with a set of indicators of indigenous people's food and agro-ecological systems developed under the multi-stakeholder Sustainable Agriculture and Rural Development Initiative. Simón Reardon and Pérez (2010) also proposed a participatory process to develop indicators to measure agri-food systems sustainability through the lens of food sovereignty in Cuba. Additionally, Ortega-Cerdà and Rivera-Ferre (2010), through a participatory process with experts and stakeholders, provided an initial set of analytical tools that facilitated the tracking and measurement of food sovereignty at national and international levels aiming to assist the process of information gathering for policy recommendations. In their work, the authors developed a pilot set of indicators to assess food sovereignty across countries, thus allowing to define the status at the country level, as well as to evaluate the impact of diverse agricultural, trade, and environmental policies in different countries. This set of indicators is the point of departure of this work.

3 Methodology

Food sovereignty set of international indicators

The selection process of indicators determines whether they will succeed or fail to accomplish their main task: to reduce a complex situation into a comprehensible one. Our point of departure was the research conducted by Ortega-Cerdà and Rivera-Ferre (2010), who suggested a pyramidal structure into categories, subcategories (attributes), and indicators. Such structure is similar to the one proposed by other social sciences studies, like the Environmental Performance Index (Hsu et al., 2013) on environmental issues and the Ibrahim Index of Governance (Rotberg & Gisselquist, 2007).

We analyzed and schematized our framework following a six steps methodology summarized in Figure 1:

a) First, we reviewed how the food sovereignty proposal has conceptually evolved since 2009 to identify whether the proposed five categories and corresponding subcategories proposed by Ortega-Cerdà and Rivera-Ferre (2010) remained relevant to the proposal.

b) Second, we identified and selected those indicators that were already compiled by those international organizations which are considered international benchmarks, such as institutions, agencies and programs related to the United Nations Organization (FAO, UNDP, and UNEP); international financial institutions (World Bank) and international economic organizations (OECD and WTO).

c) Third, we revised if the indicators were valid at the country level to verify whether each of them fulfilled the informational requirements for proper comparisons across countries and over time. Indicators that only tracked individual performance were removed from the database.

d) Fourth, we determined if the selected indicators in each category jointly reflected the objective of the whole category or whether there existed information gaps that needed to be fulfilled with additional indicators.

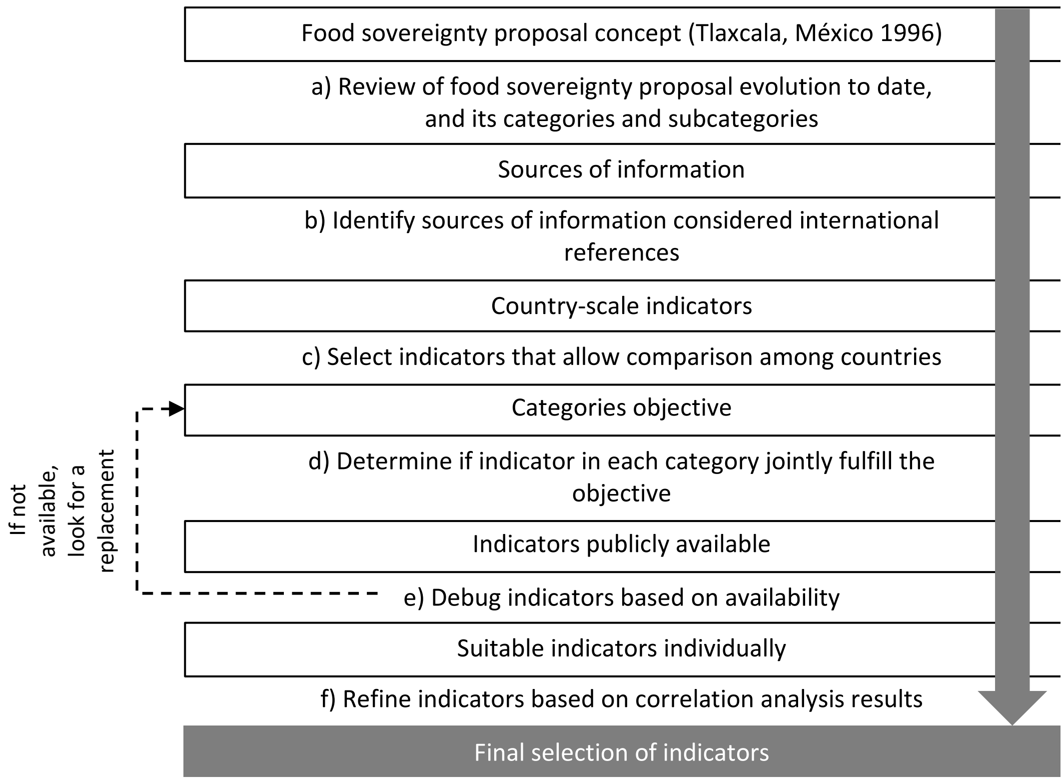

Figure 6. Indicators Selection Process.

e) Fifth, we verified whether the remaining indicators were publicly available and compiled them. Otherwise, we searched if there was an alternative indicator that could complement the information provided.

f) Finally, we performed a correlation analysis in order to refine the remaining indicators and detect those who had very little data or repeated information from some other indicators.

An important issue to consider in indicators development is the validation process. Bockstaller & Girardin (2003) proposed three kinds of validation for indicators: the "design validation" to evaluate if the indicators are scientifically founded; the "output validation" to assess the soundness of the indicator outputs, and, the "end-use validation," to be sure the indicator is useful and used as a decision aid tool. In our case, the design validation was given by Ortega-Cerdà and Rivera-Ferre (2010) who, in order to determine whether the selected set of indicators were valid to assess the food sovereignty proposal, designed a participatory process with a panel of experts on food sovereignty from different nationalities, gender and professions (from farmers to academics). As Bockstaller and Girardin (2003) stated, "for indicators, the design validation may be very important when no other possibility of validation exists (...). It consists of submitting the design or construction of the indicator to a panel of experts". The output and end-use validation of the set of indicators proposed in this article come from the source of indicators we have selected (databases from well-recognized international institutions), which ensure both the soundness of the indicators output and their potential use as a decision tool.

4 Results

Definition of categories

We set the first five food sovereignty's categories based on the five pillars proposed by Ortega-Cerdà and Rivera-Ferre (2010) and García (2003), as follows:

<u>Category One: Access to Resources</u>

"Food Sovereignty attempts to foster and to support individual and community processes on access and control over resources (land, seeds, credit, etc.) in a sustainable manner, respecting usage rights of indigenous communities, particularly emphasizing women's access to resources."

<u>Category Two: Production Models (includes processing and transformation)</u>

"Food Sovereignty attempts to increase local and diversified domestic production, recovering, validating, and divulging traditional models of agricultural production in an environmentally, socially, and culturally sustainable manner. It supports endogenous agricultural development models and the right to produce food."

<u>Category Three: Commercialization</u>

"Food Sovereignty protects the rights of farmers, landless rural workers, fishers, shepherds, and indigenous counties to sell their products to feed their local population. Such action implies the creation and support of local markets, and impulse of direct selling or at least with a minimum of intermediaries, depending on the context."

<u>Category Four: Food consumption and Right to Food</u>

"Food Sovereignty protects citizens' right to consume healthy, nutritive, and culturally appropriated food, which comes from local producers and is elaborated with agroecological techniques."

<u>Category Five: Agrarian Policies and Civil Society Organization</u>

"Food Sovereignty protects farmers' right to know, participate, and influence over the local public policies related to Food Sovereignty."

While these categories cover fundamental components of the food sovereignty proposal and hence stand as a good initial approach to measure it, in time, the proposal has included a strong call for gender equity (Tayyib et al., 2013) being gender one of the new pillars of the proposal (Dekeyser et al., 2018). Thus, the original categories left unattended a key component of food sovereignty: gender equality; and hence fell short of providing a holistic picture of the system. As Sisto (2006) pointed out: *"addressing gender and socio-economic concerns are key to promoting sustainable agricultural development and natural resources management."* The food sovereignty proposal contemplated gender equality since its early beginnings as a transversal objective, but it started to become a central issue as a result of peasant women participation in the organization and their efforts to introduce feminist perspectives within the proposal (Desmarais, 2007; Garcia Forés, 2014; Siliprandi & Zuluaga, 2014). As Puleo (2009) suggests, *"one of the most eloquent expressions of today's meeting between the feminist viewpoint and ecology is the phenomenon of protest groups of women in the struggle for food sovereignty."* In that manner, gender issues have become central to the proposal, suggesting the need to add a new category. Accordingly, we propose Gender as category six.

Attributes within food sovereignty categories and selection of indicators

The categories were divided into subcategories representing every attribute of the category's objective (Figure 2). Once achieved a clear interpretation of the concept and the principles for each category, we proceed to select the indicators (steps 3 to 6 in figure 1). In that sense, each of the categories' objectives was assessed so that every indicator added unique information, ensuring that the indicators jointly reflected the category's objective without redundancy. Ideally, every sub-category should present at least one indicator. However, the lack of publicly available information in many of them made it impossible to do so, resulting in some categories with no indicators. Blank sub-categories are shown in Table 1 as empty sub-categories. The final collection consists of 97 indicators. Almost every indicator has been standardized by dividing it with another variable to allow for comparability across countries (e.g., agricultural tractors and capital stock in agriculture are divided by agricultural area and agricultural income per capita respectively, see supplementary sources). Resulting indicators were distributed among the sixth category and the corresponding sub-category, as shown in Table 1.

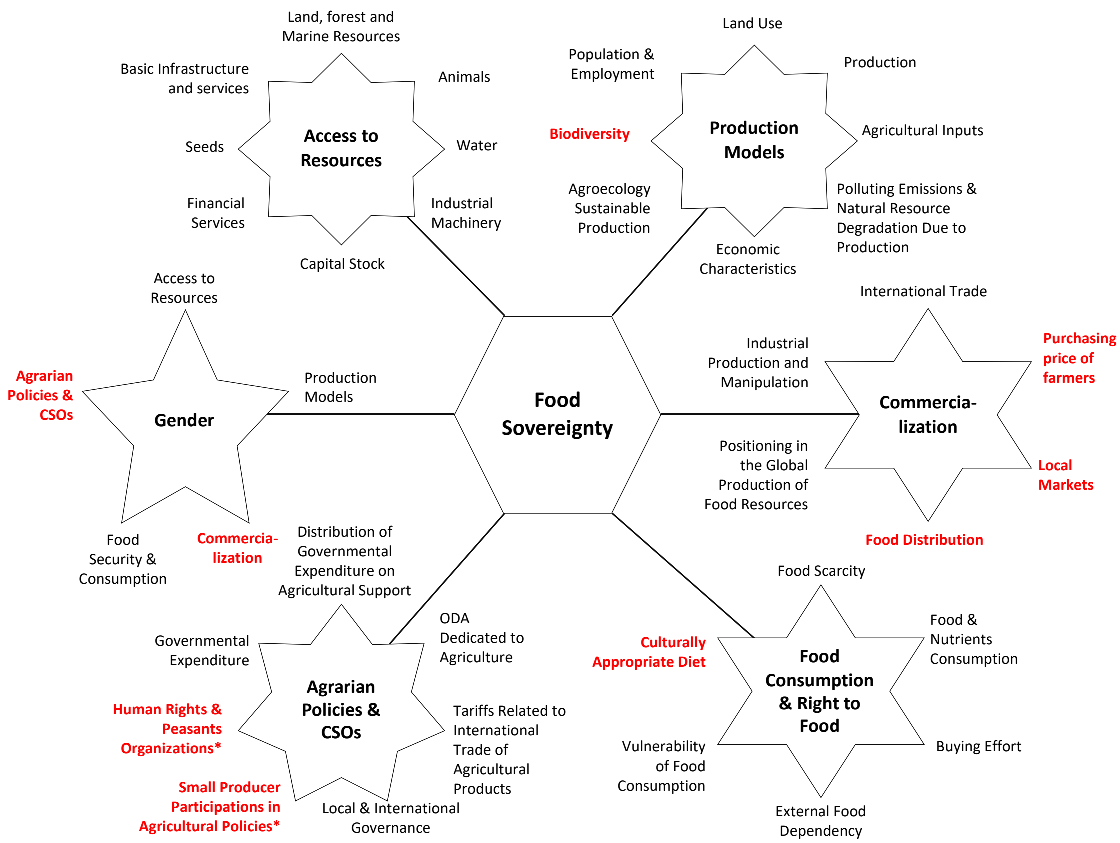

Figure 7.Categories and subcategories for the analysis of the food sovereignty proposal at the country level. Sub-categories in red means they have no indicators allocated.

Source: Adapted from Ortega-Cerdà & Rivera-Ferre (2010).

Category		Subcategories		Indicators
		Total	Empty	
1	Access to Resources	8	0	20
2	Productive Models	8	1	29
3	Commercialization	6	3	12
4	Food Security and Food Consumption	6	1	9
5	Agrarian Policies and Civil Society Organization	7	2	20
6	Gender	5	2	7

Table 1. Distribution of indicators among food sovereignty categories and subcategories.

Indicators for category one (access to resources) are designed to measure availability, access, and control of production resources by either country or region (Table 2). They also refer to resource re-distribution and identification to fight rural poverty (IFAD, 2010; Windfuhr & Jonsén, 2005). The category's objective encompasses eight subcategories: 1) basic infrastructure and services; 2) land, forest, and marine resources; 3) animals; 4) water; 5) industrial machinery; 6) capital stock; 7) financial services and 8) seeds.

Subcategory	Indicator	Period	Source
Basic Infrastructure and Services	Rural Access Index (Percentage of rural population with access to roads in all seasons)	One data few countries	WB
	Access to electricity, rural (% of rural population)	1990, 2000, 2010, 2012	WB
	Total net enrollment ratio in primary education, both sexes (percentage)	From 1990	MDG
	Proportion of rural population using an improved sanitation facility (percentage)	From 1990	UN Data
	Proportion of rural population using an improved drinking water source (percentage)	From 1990	UN Data
Land, Forest, and Marine Resources	Agricultural area (hectares per capita)	From 1961	Faostat
	Cultivated area (hectares per-capita - agricultural population)	From 1980	Faostat
	GINI Land Index	One data few countries	FAO Statistical Yearbook
	Total Land Grabs as a percentage of arable land	2012	GRAIN
	Total of crops for Biodiesel and Bioethanol production as a percentage of the arable land	From 1961	Faostat
Animals	Domestic mammals per rural inhabitant (except pack animals)	From 1961	Faostat
	Poultry animals per rural inhabitant	From 1961	Faostat
	Pack animals per square km of agricultural area	From 1961	Faostat
Water	Total internal renewable per capita (cubic meters per capita per year)	From 1961	Aquastat
Industrial Machinery	Agricultural tractors per 1000 hectares of agricultural area	From 1961 to 2009	Faostat
	Combine harvesters - threshers per 1000 hectares of agricultural area	From 1961 to 2009	Faostat
	Milking machines per head of cattle	From 1961 to 2009	Faostat
Capital Stock	Capital Stock (constant 2005 USD) per agricultural population	From 1980	WDI
Financial Services	Credit to Agriculture, Forestry and Fishing (Share of Total Credit)	From 1991	Faostat
Access to Seeds	Food and medicine biodiversity (Number of species)	2011, 2012	FAO INFOODS

Table 2. Indicators for Category 1 – Access to Resources.

Indicators for category two (production models, table 3) are designed to identify the rural population, agricultural and food production activities, land use, and resources' sustainability, which allow policy-makers to facilitate community, group, and individual-based decisions (FAO, 2013). They stand as a conservation approach by encouraging agro-ecological practices that would increase productivity on marginal soils. This could be the right instrument to conserve traditional species, diversify the local biodiversity, and preserve the environment. Indicators for this category are distributed along with eight subcategories as follow: 1) population and employment; 2) land use; 3) production; 4) agricultural inputs; 5) polluting emissions and natural resource degradation due to production; 6) economic characteristics; 7) agroecological sustainable production, and 8) biodiversity. Category two has the greatest Number of indicators. We found no indicators matching our requirements to describe the biodiversity subcategory.

Subcategory	Indicator	Period	Source
Population & Employment	Rural population (% of total population)	From 1961	Faostat
	Agricultural population (% of the total population)	From 1980	Faostat
	Total economically active population in agriculture (% of total employment)	From 1980	Faostat
Land Use	Permanent crops (% of agricultural area)	From 1961	Faostat
	Meadows and permanent pasture (% of agricultural area)	From 1961	Faostat
	Forest area (% of agricultural area)	From 1990	Faostat
	Flooded area by irrigation and natural form (% of agricultural area)	From 1973	Aquastat
	Temporary crops (% of agricultural area)	From 2000	Faostat
	Temporary meadows and pastures (% of agricultural area)	From 2001	Faostat
Production	Production of cereals per person (kg/person)	From 1961	Faostat
	Production of meat per person (kg/person)	From 1961	Faostat
	Production of fruit per person - excluding melons (kg/person)	From 1961	Faostat
	Fishery production per person (kg/person)	From 1961	FishStat
	Forest harvest rate (extraction as a % of volume forest)	From 1990	Geodata
Agricultural Inputs	Intensity of the total fertilizer use (tons/hectare of cultivated area)	1961-2003	Faostat
	Intensity of the total fertilizer use (tons/hectare of cultivated area)	From 2003	Faostat
	Intensity of total pesticides use (tons/hectare of cultivated area)	From 1990	Faostat
	Substance use for seed treatment - fungicides and insecticides (tons/hectare of a cultivated surface)	From 1990	Faostat
	Total actual renewable water resources withdrawn by agriculture (%)	From 1963	Aquastat

Continues…

Subcategory	Indicator	Period	Source
Polluting Emissions & Natural Resource Degradation Due to Production	Water pollution, food industry (% of total BOD emissions)	From 1986	WDI
	Water pollution, paper and pulp industry (% of total BOD emissions)	From 1986	WDI
	Land degradation due to the agricultural activities (% of total area)	From 2000	Terrastat
	Percentage of area equipped for full control irrigation salinized (%)	From 1983	Aquastat
	Primary forest extent (% of forest area)	From 1990	Geodata
Economic Characteristics	Poverty headcount ratio at rural poverty line (% of rural population)	From 1985	WDI
	Value added in agriculture (% of GDP)	From 1961	WDI
Agroecology Sustainable Production	Conservation agriculture area (% of cultivated area)	From 1973	Aquastat
	Organic agricultural area (% of total agricultural area)	From 2005	IFOAM, FIBL
	Forests Certified by FSC (% of total forest area)	From 2002	Geodata

Table 3. Indicators for Category 2 – Productive Models.

Indicators for category three (commercialization, table 4) focus on the right of peasants, rural workers, fishers, pastoralists, and indigenous peoples to sell their products to feed first the local population. This concept involves the creation and support of local sources of distribution, minimizing intermediaries and costs on the food chain. They could measure the "family-type" relationships between local consumers and producers, which is the result of a close and frequent liaison in terms of trade-off and responsibility, favoring powerful trust-based relations between producers and consumers. This category hence focuses on self-reliance and fair trade. It aims at measuring the concentration and distribution of products in the local and global markets and warns against monopolistic markets. This category is divided into six different subcategories: 1) international trade; 2) purchasing prize of farmers; 3) local markets; 4) food distribution; 5) positioning in the global production of food resources; and 6) industrial production and manipulation. We found no indicators matching our criteria to describe the purchasing prize of farmers, local markets, and food distribution subcategories.

Subcategory	Indicator	Period	Source
International Trade	Agricultural raw materials exports (% of merchandise exports in dollars)	From 1962	WDI
	Agricultural raw materials imports (% of merchandise imports in dollars)	From 1962	WDI
	Food exports (% of merchandise exports in dollars)	From 1962	WDI
	Food imports (% of merchandise imports in dollars)	From 1962	WDI
	Fishery imports (% of imports, in dollars)	From 1976	Fishstat Faostat
	Fishery exports (% of exports, in dollars)	From 1976	Fishstat Faostat
	Imports of forest products (% of imports, in dollar terms)	From 1961	Faostat Forestat
	Exports of forest products (% of exports, in dollar terms)	From 1961	Faostat Forestat
Industrial Production and Manipulation	Food, beverages, and tobacco (% of value-added in manufacturing)	From 1990 to 2009	WDI
Positioning In The Global Production Of Food Resources	Cereal production (% of world production)	From 1961	Faostat
	Meat production (% of world production)	From 1961	Faostat
	Fishery production (% of world production)	From 1961	Fishstat

Table 4. Category 3 – Commercialization.

Indicators for category four (food consumption and the right to food, table 5) are designed to quantify food insecurity in the country or region, focusing primarily on the hunger and the poor; it measures the nutritious status of people by comparing their daily nutritious intake with their minimum requirements. Likewise, it measures the degree of dependence and vulnerability of a country or region by providing information on their external food dependency and the concentration of their dietary energy supply. There are six subcategories that represent every aspect of food security: 1) food scarcity; 2) food and nutrient consumption; 3) buying effort; 4) external food dependency; 5) vulnerability of food consumption; and 6) culturally appropriate diet. We found no indicators matching our requirements to describe the culturally appropriate subcategory.

Indicators for category five (agrarian policies and civil societal organization) attempt to account for those political conditions which are critical to the food sovereignty proposal (Palomino Amador, 2012); they also capture the importance given to agriculture through public and private enterprises, and the right of peoples to decide their own agricultural policies.

Subcategory	Indicator	Period	Source
Food Scarcity	Prevalence of undernourishment in total population (%)	From 1991	WHO UNICEF
	Children under 5 moderately or severely underweight (%)	From 1990	MDG
	Depth of the food deficit (kilocalories per person per day)	From 1992	WDI
	GINI coefficient for food consumption (dietary energy consumption)	One data few countries	FAO Statistics Division
Food & Nutrients Consumption	Average dietary energy supply adequacy (%) (3-year average)	From 1990	Faostat
	Average protein supply (g/capita/day) (3-year average)	From 1990	Faostat
Buying Effort	Share of food expenditure of the poor (%)	From 1989	Faostat
External Food Dependency	Cereal import dependency ratio (%) (3-year average)	From 1989	Faostat
Vulnerability of Food Consumption	Share of dietary energy supply derived from cereals, roots, and tubers (%) (3-year average)	From 1990	Faostat

Table 5. Category 4 – Food Security and Food Consumption.

Category five focuses on the estimated government support for both producers and consumers, as well as in the general service of agriculture. It warns from subsidies going directly to trading and storage companies and tries to capture agricultural tariffs so as to measure trade obstacles. Likewise, this category pays special emphasis on the development assistance given or received to create awareness about the effective use and distribution of resources. Indicators in this category are distributed in seven subcategories: 1) governmental expenditure; 2) distribution of governmental expenditure on agricultural support: 3) official development assistance dedicated to agriculture: 4) tariffs related to international trade of agricultural products; 5) local and international governance; 6) small producer participation in agricultural policies and 7) human rights and peasants' organizations. We found no indicators matching our criteria to describe the small producer participation in agricultural policies and the human rights and peasants' organization's subcategories.

Subcategory	Indicator	Period	Source
Governmental Expenditure	Percentage of agricultural in total spending (%)	From 1980	IFPRI
	Percentage of agriculture in total spending (% of National Currency)	From 1980	IFPRI
	Public agricultural R&D expenditures (% of agricultural GDP)	From 1981	ASTI
Distribution of Governmental Expenditure on Agricultural Support	Total support estimate (TSE) (€ millions)	From 1985	OECD
	Producer support estimate (PSE) (% of value of production)	From 1985	OECD
	Producer support estimate (PSE) (% of TSE)	From 1985	OECD
	Consumer support estimate (CSE) (% of TSE)	From 1985	OECD
	Estimation of general services support agriculture (GSSE) (% of TSE)	From 1985	OECD

Subcategory	Indicator	Period	Source
Official Development Assistance Dedicated to Agriculture	ODA received or contributed to agriculture, forestry and fishing ($ million)	From 2005	OECD
	ODA received or contributed to Food Aid ($ million)	From 2005	OECD
Tariffs Related to International Trade of Agricultural Products	Final bound simple average for agricultural products	From 2008	WTO
	MFN (Most Favored Nation) tariff, simple average for import duties for agricultural products	From 2008	WTO
	Trade weighted average tariffs for agricultural products	From 2008	WTO
Local and International Governance	Voice and Accountability	From 1996	WB
	Political Stability and Absence of Violence/Terrorism	From 1996	WB
	Government Effectiveness	From 1996	WB
	Regulatory Quality	From 1996	WB
	Rule of Law	From 1996	WB
	Control of Corruption	From 1996	WB
	KOF Index of Globalization	From 1970	Dreher et al. (2008)

Table 6. Category 5 – Agrarian Policies and Civil Society Organization.

Indicators for category six (gender) are grouped in subcategories that represent each of the previous five categories to determine whether the gender dimension is considered along with the entire framework. A holistic approach cannot be complete if the differentials given by gender and ethnicity in every dimension are not recognized. Differential access to and control of resources, knowledge, tasks, and decision-making are all dependent on sex, age, socio-economic group, the level of formal education, ethnicity, agro-ecosystem, and customary norms (Sisto, 2006). Ideally, this category would consist of indicators providing the perspective of gender equity for each of the subcategories developed in the other five categories. Yet, due to the lack of available data, we have tried to include those gender-sensitive indicators with the potentiality to the international comparison and with the greater number of data available (Table 7). For the moment, only categories one, two, and four have representation in this category.

Subcategory	Indicator	Period	Source	Complement Category
Population & Employment (Gender)	Female population (% of total population)	From 1961	Faostat	2
	Employees, agriculture, female (% of female employment)	From 1980	WDI	2
	Female economically active population in agriculture (% of total female employment)	From 1980	Faostat	2
	Wage and salaried workers, female (% of females employed)	From 1980	WDI	2
Basic Infrastructure and Services (Gender)	Total net enrollment ratio in primary education, girls (percentage)	From 1990	MDG	1
Food Scarcity (Gender)	Prevalence of anemia among pregnant women (%)	From 1990	Faostat	4
	Children aged <5 years underweight (%) - Female	Few data from 1970	WHO	4

Table 7. Category 6 – Gender

5 Discussion

In developing this food sovereignty indicators database at the international level, we have performed some changes to the initial set of indicators proposed by Ortega-Cerdà and Rivera-Ferre (2010). Main differences are explained principally because 1) the indicators didn't meet our criteria; 2) they are no longer available either because the calculation methodology has changed recently, or because the indicator that was first considered was no longer updated, or 3) we found new indicators that better suited the category objective. Those differences may vary specifically for every category and subcategory.

In category 1 (access to resources), we highlight three key points: the first one is that we kept only one indicator in the water section, the one that shows water availability, and we reallocated the remaining indicators in different subcategories or categories accordingly. The second change is that we added a new indicator regarding credit to agriculture that was not considered in the initial set. The third change refers to access to seeds, where most of the crucial information is not publicly available. Few multinationals maintain control over both the seeds and the information, which makes access to information very difficult for independent researchers. Indeed, the double role of seeds as food and means of production makes them a very controversial component of the food system (Kloppenburg, 1988). The seeds market in 2011 was valued at approximately 45 billion dollars (ISF, 2012). Notwithstanding, we have decided to keep the category with only one indicator, given the importance of this subcategory. Only some data are available about seed concentration gathered by

NGOs (see ETC (2012)), but the methodology used is not clearly explained, and so we have not included their data in our database. Also, data about local seeds and the relevance for peasants do not exist. Finally, despite the lack of data, we have maintained two important indicators that add transcendental information to the category's objective: Rural Access Index and GINI land index. Both of them show few data for some countries; in the case of the first one, it covers connectivity of rural areas and is calculated once (between 1993 and 2004) for more than 200 countries and territories. The later reflects the concentration of land ownership, and was calculated once for 184 countries and territories, in years ranging from 1994 to 2002.

In category two, Ortega-Cerdà and Rivera-Ferre (2010) considered indicators in the subcategory agricultural biodiversity and marine assessment, but we have removed them because they are not available. Other indicators removed included those expressed as production indexes and those that refer to companies' market share; both are important for individual analysis but do not allow for country comparisons. Furthermore, we faced a major change in this category as a result of changes in the main databases used: FAO changed the methodology to measure the use of fertilizers in 2003, averting time analysis between databases, one from 1961 to 2003 and the other from 2003 to present. We kept both databases as two different indicators.

The major challenge for category three (commercialization) was the lack of information concerning local and national markets (Table 4). The indicators for this category focus on the analysis of the international flow of food at the country level, making it difficult to know the specific problems for each country. There are several specific studies that can be used for individual analysis, but we have not identified an indicator that shows a comparison of internal food commerce. Another important informational constraint attributable to this category is the lack of a specific indicator, comparable across countries, on the purchasing price of farmers. Originally, we considered the "price paid to farmers in terms of dollar per ton of the top five production goods in each country," but differences in food production preferences for each country preclude an international comparison. Finally, the subcategory of "food distribution" is also empty; we could not find a suitable indicator or group of indicators that reflect distribution issues at the international level.

Category four (food consumption and the right to food, table 5) has suffered the most relevant modifications in terms of the number of indicators. In 2011 FAOSTAT changed the Food Security Database to improve the hunger estimates in a way that reflected the complexity of the problem. For that reason, some indicators considered by Ortega-Cerdà and Rivera-Ferre, 2010) were left out of the final database and replaced by new ones. For example, we had considered a subcategory "vulnerability of food consumption" aimed at analyzing the country's dependency on the three food groups to obtain daily requirements of energy, protein, and fat. However, indicators of food consumption patterns were no longer available on FAO's databases, so the subcategory included a single indicator "share of dietary energy supply derived from cereals, roots, and tubers (%)." The set of indicators in this category missed the subcategory of "culturally appropriate diet" since it is a qualitative analysis that has been done at regional levels but does not have a reliable quantitative assessment at the international level that could be used for the purposes of this work. Finally, despite the lack of data, we decided to keep the "GINI coefficient for food consumption" for its uniqueness as it shows the inequality in the consumption of food.

Category five includes those indicators regarding the development of agricultural policies, one core objective of the food sovereignty proposal, and governance aspects (Table 6). Category five did not originally include indicators regarding civil society organizations because initially, food sovereignty was mostly centered on the peasants' participation in the development of agricultural policies, and thus, was focused on peasants' organizations. In time, however, and with the increased support of new actors, the proposal has extended the need for participation across the whole society, stressing the necessity to have not only strong peasants' organizations but also proactive civil society in general (Calle Collado et al., 2011). The main challenge faced in this category was data availability since there are limited data sources, and they do not entirely reflect the main objective of the category, which are the evaluation of these policies and the involvement of producers in decision-making. Data sources provide limited information; for example, the Organization for Economic Co-operation and Development (OECD) contains only countries members and few other developing countries; and the World Trade Organization (WTO) only published the last available data on their web page. Given the emphasis given to direct democratic participation by the food sovereignty proposal, we considered that social organization had to be a part of this category, so we included a new subcategory with a set of indicators proposed in Palomino Amador (2012) to measure local and international governance, which includes the World Bank's Governances indicators (Kaufmann et al., 2010) and the KOF Index of Globalization (Dreher et al., 2008). Indicators for two subcategories are missing; those reflecting small producers' participation in agricultural policies and those showing human rights and peasant organizations in every country. Both categories are essential for the food sovereignty proposal, but unfortunately, there is no information available at the international level.

With respect to category six, despite the efforts of some multilateral organizations to recognize the importance of gender-sensitive indicators (GSI) with the aim of creating awareness of the different impacts of a development intervention on men and women given their social-economic and cultural differences, there is still very limited focus on GSIs on agricultural, food and nutrition statistics (Tayyib et al., 2013) resulting in a lack of GSI at international level. Thus, there are not enough quantitative gender studies related to food sovereignty to set a complete framework on the matter. There are some projects that promise to fulfill this informational gap of information, such as the Women's Empowerment in Agriculture Index (WEAI) developed by USAID for some countries since 2012. But many of these efforts are still in progress and do not have any immediate result to be used in this work.

As expected, there are a series of constraints for the consecution of the current research that hindered the achievement of sufficient indicators in some of the categories. First, gathering indicators of different nature (social, environmental, and economic) posits two main difficulties: (1) It may lead to assume that the greater the number of indicators in the framework, the lower its individual importance; and (2) despite the enormous amount of resulting indicators, there are certain aspects of food sovereignty that cannot be tackled because of informational gaps (in other words, for certain aspects the indicators do not clearly reflect the essence of food sovereignty as a whole, e.g., local markets and GSI).

Second, there are many private interests in the agri-food system that make it difficult to access information across countries. For example, we found that most databases offering information on seeds were private. Similarly, countries that do not belong to international organisms of higher organization level offer scarcer information in comparison to others, such as OECD countries, for instance, offering more data than non-OECD.

Third, political instability obstructs to gather of consistent time series data. Plus, country information should be based on detailed information collected at the field level by different government agencies; for that reason, countries facing sociopolitical conflicts or with poor infrastructure often fail to report accurate information to multilateral organizations. On the other hand, the geopolitical division of many countries has changed over the past 50 years, particularly since the early 90s. Monitoring the performance of the information beyond this date is a complicated task.

Finally, the lack of strong and stable gender-related databases, as well as the lack of a gender perspective in data gathering at the international level, makes it very difficult to assess the gender dimension on food sovereignty policies. Also, peasant women calling for food sovereignty does not claim for a gender-focus of policies, but for a feminist focus, which also implies not only gathering GSI but also looking for indicators that put at the center of the discussion both productive and reproductive activities. The latest refers to those activities that sustain life (Pérez Orozco, 2014; Shiva & Mies, 1998; Siliprandi & Zuluaga, 2014) which is considered probably the most important difference between industrial agriculture (focused on growth and capital accumulation) and peasant agriculture (focused on the reproduction of the system within the agroecological context) (Chayanov, 1991).

Despite these potential difficulties, some of which are inherent to the process of quantifying qualitative factors, there are at least three target groups that can benefit from this work. First, policymakers and non-governmental institutions could benefit from the adoption of an objective tool that allows time comparison across regions or countries, and so facilitates the assessment of changes in agricultural policies as well as the degree of sustainability of the food system from a food sovereignty perspective. For instance, since one of the criteria for the eligibility of indicators is the availability of publicly time series, these indicators can be used either jointly or individually (as categories) as a reference to monitor specific public policy effects on time. Second, private institutions and actors can use this set of indicators as a ground floor to establish specific action niches for the various stakeholders (farmers, fishermen, consumers, policymakers, etc.), facilitating comparability and decision-making. Finally, scholars, who can use the entire collection or a part of it as instrumental variables for further statistical research, such as assessing how changes in any given variable impact another variable with different nature; and in this manner, create connections between economic variables and environmental or social ones in agri-food systems. To facilitate access to the indicators, we have developed an on-line database publicly available (https://foodsovereigntyindicators.uvic.cat/).

6 Potential applications of the database

There are many potential applications for this database. This may include the calculation of the status of food sovereignty at regional (Çomak, 2012; Mohammed, 2012; Ruiz-Almeida, 2012) and world level (Oteros-Rozas et al., forthcoming). The database could also be used to create a composed food sovereignty index (FSvI). We have made some efforts in that direction (Comat, 2012), but we see some problems in this particular regard. To develop a food sovereignty index, we have followed the OECD Aggregated Environmental Indices (Goldberg, 2002), particularly synoptic indices, which claim to give a comprehensive view of very complex things, such as food sovereignty. The food sovereignty index would be composed of the sum of the different indicators of all the six categories of food sovereignty. The aggregation methodology consists basically of the addition of variables or units with similar properties in order to come up with a single number that represents the overall value. It involves four basic steps: the selection of variables, transformation, weighting, and valuation. The first two steps have been carried out in the development of this database. The most critical step, though, is weighting: It is recognized that there may be legitimate differences of opinion regarding the relative importance of each category as well as each indicator from country to country. For instance, access to resources might be more important for developing countries, while agrarian policies could be more important for developed ones. Therefore, for the sake of neutrality and objectivity, an equal weighting could be assumed for each category, being a simple average of their standardized indicators. However, this gives, in fact, a partial explanation of reality. It helps for comparisons, but it does not help in describing a particular country's situation with respect to food sovereignty. To that effect, we propose that weightings should be done case by case and determined based on expert judgments and stakeholders' participation, having in consideration the relative importance of each indicator and category for each country or region. Regarding the valuation step, every indicator would have attached a binary value as either positive or negative, and because a valuation process needs the judgments of experts, like in the weighting process, an FSvI following this methodology would serve more as a ranking mechanism than as a tool for providing an objective, quantifiable value. An alternative solution could be to set optimal values for each indicator and then use the "proximity to target" methodology, as it is done, for instance, in the Environmental Performance Index (EPI) calculations. Other methodologies, like Fragile States Index (FSI) and Democracy Index (DI), classify countries according to the final Number: the FSI in extreme, high, medium and low risky countries; while in the DI in full democracies; flawed democracies; hybrid regimes; and authoritarian regimes.

Equations to develop the food sovereignty index based on this database would be, for each of the categories, as follows:

$$C_k = \frac{1}{n_k} I_1 + \cdots + \frac{1}{n_k} In_k$$

Being the composed index as follows:

$$Food\ Sovereignty\ Index = \frac{1}{6} \sum_{k} C_k$$

Where C refers to the categories and k=1,2…6 (the six categories) and Ink is the Number of indicators in each category k.

Other uses of this database may include the analysis of food flows and its relationship with the region's vulnerability to international markets change; correlation analysis among variables to determine whether the six categories still stand in every region. The usefulness of this database is also applicable to the assessment of the sustainability of the agri-food system as a complex socio-ecological system, which can be done either through correlation analyses or network theory.

7 Concluding Remarks

Given the complexity of agri-food systems, which we understand as complex socio-ecological systems, qualified with far-from-equilibrium states, co-evolution of system components, self-organizing properties, non-linear dynamics, multivariable structure, high levels of uncertainty, control of limiting factors, and cross-scale relationships in time and in space (Rivera-Ferre et al., 2013); the quantitative analysis with regard to the sustainability of the agri-food system entails a number of limitations that may discourage this kind of research. However, as Holling (2001) proposes, "we must work in defining what is known, what is unknown and what is uncertain because we always stick to the better judgment and not to the best certainty." Currently, there is a lack of consensus regarding what specific characteristics a sustainable food system should have and how to define it. Thus, different actors hold their own definitions. Small farmers have elaborated the food sovereignty proposal as a potential option to develop their vision of how a sustainable food system should look like.

The food sovereignty proposal offers a political framework to develop sustainable agri-food systems from the perspective of small farmers. Nonetheless, to date, there are not enough quantitative studies to analyze the efficiency of the proposal in achieving such an objective. The growing acceptance of this concept as a robust and viable alternative to eradicate undernourishment, promote rural development, and mitigate the environmental crisis, evidences the critical relevance of this research.

The set of indicators here presented, hence, is motivated upon the adoption of food sovereignty proposal in several countries, and by some multilateral organizations, and seeks to stand as groundwork that contributes to the quantitative and qualitative analysis of the agri-food system as a whole, with the aim to put forth tools that allow to measure and interpret the system functioning and its degree of sustainability from a complex-systems perspective.

Throughout the development of this work, we faced difficulties in accessing information, either because the information does not exist anymore or because it is in the hands of private entities that constrain public access. These difficulties show how the measurement of a complex socio-ecological system through indicators is not an easy task; indicators are continuously evolving and respond to specific policy's needs and market interests. We are dealing with a dynamic set of indicators that requires constant monitoring and update effort. By presenting a collection of indicators, we intend to give flexibility for the application of this work since there are several ways in which these indicators can be used.

The work here presented not only allows for further research aimed at measuring the sustainability of the agri-food system from a food sovereignty perspective. It also emphasizes the need to analyze agri-food systems holistically by advancing a set of indicators capable of adequately describing the status of food systems at the country level and including the maximum amount of information regarding various countries' agri-food systems description, with a standardized set of indicators as a reference point.

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Chapter 2. From practice to theory: Food sovereignty as a concept to assess the sustainability of the agri-food system

Abstract

In this work, we advance the concept of food sovereignty as a conceptual framework to analyze agri-food systems' sustainability following the steps proposed by Jabareen (2009) to build conceptual frameworks. In previous work, we advanced the first four phases: identifying data, selecting, categorizing, and processing such data, identifying and naming concepts, and the main attributes, characteristics, assumptions, and roles. Here we complete the process with the other phases by integrating similar ideas and synthesizing concepts into a theoretical framework, validating the conceptual framework, and rethinking the conceptual framework as a dynamic phenomenon. To integrate similar concepts, we follow the four agrarian questions (agriculture, quality, environmental, emancipatory) and the three fundamental outcomes of sustainable agri-food systems: Food and nutrition security, environmental resilience, and social well-being. Here, we analyze the interconnections among food sovereignty attributes and synthesize them to create the conceptual framework. We conclude by offering the concept of "Food Sovereignty" as a complete and valid framework to measure sustainability.

1. Introduction

Discussion around agri-food systems sustainability is at the center of global agreements and initiatives such as the Sustainable Development Goals (SDGs), with several reports analyzing food systems from an SDGs perspective. Just to mention a couple: the Economics of Ecosystems and Biodiversity initiative relates the agri-food system with each SDG (TEEB, 2018)[9], and the Transforming Food and Agriculture to achieve the SDGs Report (FAO, 2018). The InterAcademy Partnership (IAP, 2018) and the European Academy of Sciences (SAPEA, 2020) have produced in-depth reports on Food, and the recently approved farm to fork strategy also has the food system's sustainability at the core of its objectives (European Commission, 2020). The latter is not surprising since the current

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[9] See http://www.teebweb.org/sdg-agrifood/annex-1/ (visited on: 26/04/2020)

global agri-food system has shown countless inconsistencies as proof of its unsustainability to feed the growing population (IAP, 2018) equitably. A clear example is the still existence of 618 million people with hunger, two billion overweighed people (FAO, 2019), of which around 700 million with obesity by 2018, and about two billion people with some kind of micronutrient deficiency, in a world where Food is produced in abundance (Holt-Giménez et al., 2012). In fact, as of this date, many malnutrition factors are now considered *the leading risk factors for deaths worldwide* (FAO et al., 2019; Naghavi et al., 2017).

An associated concern to these inconsistencies is that food distribution channels follow economic incentives, leaving aside the human right perspective to pursue adequate Food and nutrients worldwide. Eating is a fundamental human right, but paradoxically Food is one of the most traded commodities in a global market based on competition[10], leading to an inadequate distribution to the final consumers (Berners-Lee et al., 2018; Sukhdev et al., 2016). Holt-Giménez et al. (2012), for instance, accurately pointed out that the primary driver of hunger, and we would add of malnutrition in general, has not been scarcity, but poverty and inequality.

These facts show the "inefficiencies" of the global food system around food security, the primary food systems outcome. However, if we expand the perspective towards ecosystems or human welfare, then the number of impacts grow all around the world, from the very local (e.g., soil management) to global scales (e.g., globalization) (Gomiero, 2019).

Along with the current inefficiencies of the global agri-food system, there are a series of recent phenomena that further challenge its performance: climate change and global warming effects, growing demand as a consequence of population growth and concentration in urban areas, the exponential loss of biodiversity, geopolitical issues, pandemics, among many others (IAP, 2018).

Not only do these events challenge its ability to reach the food security goal, but they also highlight the need to implement a set of policies that encompasses the impacts that the global agri-food system can exert at different scales.

Over the past years, some alternatives have emerged to assess agri-food systems' sustainability; hence, potentially mitigating the aforementioned adverse effects and improving human well-being. Those alternatives and methods emerge from many different perspectives. From a local-scale

[10] See http://www.fao.org/waicent/faoinfo/economic/faodef/faodefe.htm for more detail in food commodities groups.

perspective, Carlsson et al. (2017) proposed a community-level process based on the Framework for Strategic Sustainable Development (FSSD) that facilitates policy planning at that level, recognizing the lack of tools to land global-scale conceptualizations into actions at the community level. DeClerck et al. (2016) proposed a conservationist approach to agricultural landscape management from a conservation perspective. Another interesting approach is those in Tribaldos et al. (2018), which adds a usually obviated dimension, the link between diet and sustainability. The authors discussed what the belief is the critical link: food security, the right to Food, reduction of poverty, and inequality, environmental performance, and resilience.

Those perspectives are just a few examples of the many discussion streams that exist nowadays. Béné et al. (2019) analyzed some of the main narratives around the food systems' unsustainability by observing the various outcomes (e.g., malnourished people, rural poverty) as independent events; thus, failing to provide adequate insight into the food systems' dynamics (Clapp, 2009), and letting out of the scope the complexity of the system.

8 Building sustainable agri-food systems

To better understand sustainable agri-food systems, we must first define an agri-food system and later analyze its elements and scope.

Agri-food systems' perspectives

The concept of food systems dates back to several decades (SAPEA, 2020). It has gained prominence in recent years (Foran et al., 2014; Lang & Barling, 2012; Rivera-Ferre, 2012; Westengen & Banik, 2016) when leading experts started to approach the idea (IAASTD, 2009; iPES food 2015). Traditionally, the bulk of studies was centered along the food supply chain, where scholars attempted to develop simplistic theoretical models to find universal solutions on public policies that frequently failed (Ostrom, 2009). More recently, some authors have proposed systemic approaches to study and manage agri-food systems by contemplating and integrating variables that delve into details of distribution, access, and utilization of Food (El Bilali, 2019; Nelson et al., 2016; Ruiz-Almeida, 2012; Sandhu et al., 2019; Vallejo-Rojas et al., 2016).

Ericksen (2008) stated the relevance of analyzing "the food system's interactions with global environmental change and evaluating the major societal outcomes affected by these interactions: food security, ecosystem services, and social welfare." In her analysis, the system's leading emerging property is Food and human nutrition across the bio-geophysical and social environments, which define the relationship between the human being and its environment. All these interactions are what Ostrom (2009) described as a complex socio-ecological system (SES), where multiple subsystems and internal variables continuously interact, and through these interactions generate consequences in the form of outcomes, which eventually could also feedback at the subsystems levels. Therefore, to promote sustainability, we must analyze the systems' outcomes individually and their interactions and the results of such dynamics.

In agri-food systems, interactions occur amongst agricultural, environmental, and socioeconomic systems multidimensional in time and space (Vallejo-Rojas et al., 2013). To address this complexity, Ericksen (2008) proposes a framework in which implicit recognition that such systems are managed, either directly or indirectly, for the human benefit (i.e., ecosystem services). That one set of services could be favored (e.g., food production) at the expense of another set (e.g., quality of water for fish); hence these objectives can conflict with each other.

This framework contemplates four main activities that take place within the food system (): (i) food production, which refers to all the processes that are intrinsically related to raw material production, those related to agriculture and animal breeding; (ii) processing and packaging, which incorporates those activities related to raw material transformation; (iii) distribution and sale, which considers such activities through which Food is moved from a place to another, and (iv) consumption, which refers to those activities that range from food selection to its cooking and final use.

This framework's final expected result would be a benchmark to measure food security in most FAO dimensions except for "stability," which was added later[11]. Ericksen argues that those activities contribute to achieving food security and the welfare of both the population and the environment. Together, those outcomes can be understood as the agri-food system's sustainability since they represent the three remarkable aspects of sustainability: economy, environment, and society. Nonetheless, in this framework, these contributions are recognized as secondary results that may or may not be achieved, being food security the primary outcome.

[11] The Declaration of Rome on World Food Security define the three basic dimensions in 1996: access, availability and utilization. Access would refer to the ability from a unit to get a hold of food in with the quality and quantity required. Availability refers to the quantity, quality and type of food that a unit has at its disposal. Utilization, in turn, deals with the household capacity to benefit from food consumption. Finally, in 2009 the concept of stability was included, since it brings the time dimension to the concept and deals with the ability to withstand shocks to the food chain (Berry et al., 2015).

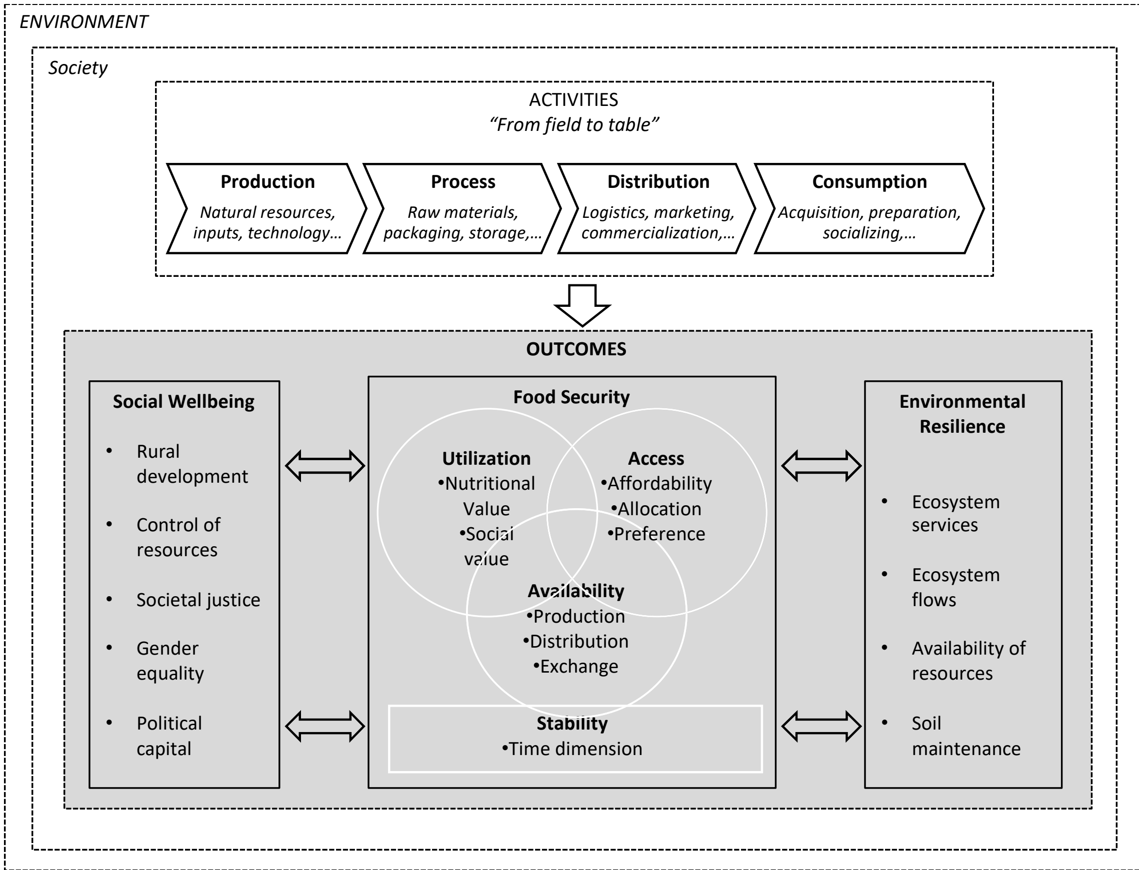

Figure 8 Components of the Agri-Food System conceptualized as a CES and its primary outcomes.
Source: Adapted from Ericksen (2008)

Vallejo-Rojas et al. (2013) completed Ericksen's framework by incorporating institutional aspects and actors' agency into analyzing local agri-food systems. These authors centered their study on the framework initially put forth by Ostrom by detaching the complex system into dynamic subsystems that also affect the processes at different scales.

However, it is not possible to address the sustainability of food systems without introducing a temporal dimension that incorporates the concept of intergenerational justice, as stated in the Brundtland Commission Report (1987). This report claims that policies for achieving sustainability should aim at equally attending to the current needs and challenges, without damaging the environment nor compromising in any way the ability of future generations to meet their own necessities. The latter applied to the agri-food systems implies that a sustainable agri-food system is the one that achieves the present system's outcome without compromising achieving such outcomes in the future.

The concept of intergenerational justice also puts forth the notion of interterritorial solidarity, which implies that it is impossible to achieve sustainable food systems in one territory at the expense of other regions' ecosystems (SAPEA, 2020). Thus, despite the growing number of studies and reports addressing food systems' sustainability, there is no accepted definition of a sustainable agri-food system or how it should be conceptualized.

Béné et al. (2019) explored the narratives around the "unsustainability" of the agri-food system. They showed that researchers and analysts are still struggling to understand and apply sustainability concepts to the agri-food systems. Its definition has been interpreted in different ways, some of them based on relatively narrow applications. Many visions hold their meaning, sometimes contradicting each other, according to their narratives and perspectives (Béné et al., 2019; Ruiz-Almeida & Rivera-Ferre, 2019). To understand the scope and implications of agri-food systems, we should first embrace their complexity and the fact that agri-food systems can be approached through diverse and often divergent conceptual that derive from different mental models perspectives (Rivera-Ferre et al., 2013; SAPEA, 2020). So, it would be useful to undertake a pluralist, interdisciplinary inquiry concerning the meanings of and possibilities for improving the system's primary outcomes (Foran et al., 2014; Rivera-Ferre, 2012).

In this chapter, based on the work of Ruiz-Almeida and Rivera-Ferre (2019), we build a conceptual framework around the sustainability of the agri-food systems following the methodology offered by Jabareen (2009), as a starting point and from the perspective of food sovereignty.

Methods

Jabareen (2009) proposes a methodology to build a conceptual framework by identifying the main components to create a consistent concept. The author defines a conceptual framework as: *"a network of interlinked concepts that together provided a comprehensive understanding of a phenomenon or phenomena"* and stated eight phases (Table 1) to define a sound conceptual framework.

Our phenomena of study are agri-food systems and the elements which define their sustainability. The first five phases cover what Ruiz-Almeida and Rivera-Ferre (2019) presented in their research "Internationally-based indicators to measure Agri-food systems sustainability using food sovereignty as a conceptual framework." In their work, the authors mapped, identified, and categorized 97 indicators distributed in six categories: 1) access to resources; 2) productive models; 3) commercialization; 4) food consumption and the right of Food; 5) agrarian policies and civil society

Phase	Definition
1	Identifying literature review, source of data, empirical data, and practices.
2	Selecting data and categorized them by discipline and scale.
3	Processing data by identifying and naming concepts.
4	Identifying the main attributes, characteristics, assumptions, and roles.
5	Integrating concepts that have similarities.
6	Synthetizing concepts into a theoretical framework
7	Validating the conceptual framework
8	Rethinking the conceptual framework as a dynamic phenomenon

Table 8 - Jabareen's Methodology Phases

Source: Adapted from Jabareen (2009))

The last three phases comprise building the conceptual framework, its consistency, and the need for validating and rethinking such a framework. Over the next sections, we follow this methodology's main ideas to present food sovereignty as a conceptual framework approach to address the agri-food system's sustainability.

9 Elements to pursue sustainable agri-food systems

The agri-food system's sustainability is defined by the elements that shape the relationships, interactions, and activities that coexist. Each component that defines the system's consistency is inseparable despite its distinctiveness (Deleuze & Guattari, 1996).

In this sense, Constance (2008; 2014) presents a holistic approach that tackles all sustainability dimensions throughout the different activities of agri-food systems by settling four essential questions. First, the *agrarian question* aims to understand the relationship between agriculture and peasants' structures and rural communities' well-being, focusing on labor relations. Second, the *environmental question* seeks to understand the relationship between agriculture and the environment's quality to know the impacts of agriculture on the environment. Third, the *food question* refers to the relationships between the agri-food systems and their food quality; this quality perspective is more closely related to nutrition. Fourth and final, the *emancipatory question* delves into the relationship between agri-food systems and social justice and civil rights.

Each question is related to at least one component of Ericksen's agri-food system, as shown in Figure 2. Furthermore, each question focuses on one of the system outcomes, and thus, the questions themselves stand as useful tools to achieve such an outcome.

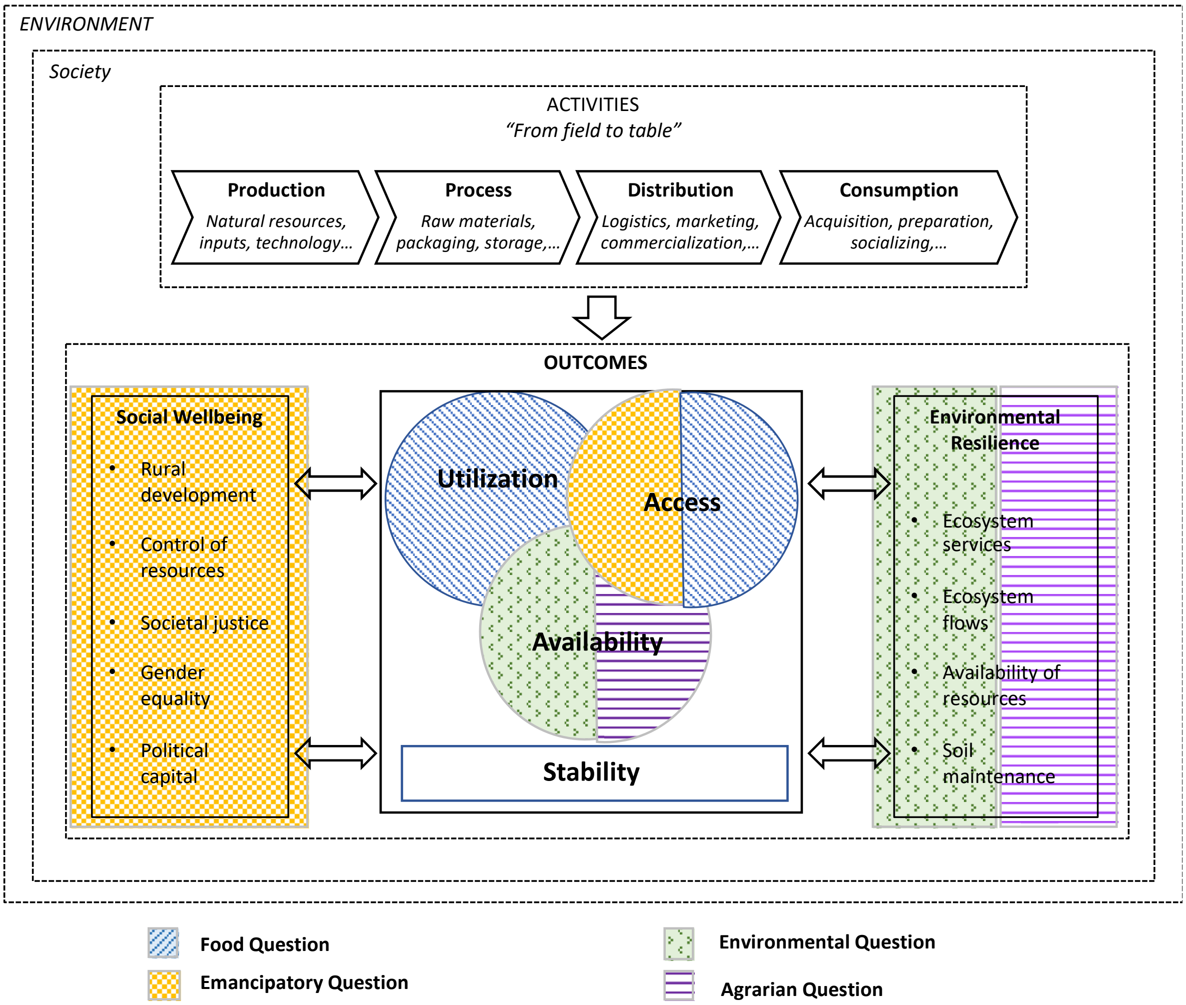

Figure 9 Components of the Agri-Food System and its relationship with Contance's Questions conceptualized as a CES

Source: Adapted from Ericksen (2008)

Constance (2008) identified through the emancipatory question that "the problem" of the agri-food system's unsustainability lies in the interactions among the environment, family farms operations, and rural communities. Such an answer emerges from a political-economic critique of industrializing agriculture and promotes sustainable agriculture. The path towards sustainability begins supporting the development of a more just agri-food system.

In developing a conceptual framework of the food system's sustainability from a food sovereignty perspective continuing Ruiz-Almeida and Rivera-Ferre's (2019) work, it is necessary to integrate food sovereignty with similar concepts agri-food systems sustainability. From a theoretical perspective, and following a food systems approach and complexity science, food sovereignty brings together all different systems' components into a framework organized around justice and solidarity concepts. It also incorporates political ecology and feminism components.

Ruiz-Almeida and Rivera-Ferre (2019) started addressing Jabareen's fifth phase, putting together the concepts framed under the food sovereignty pillars stated in Nyéléni's declaration summarized in Dekeyser et al. (2018; Table 2).

Each of those pillars is directly related to at least one of the system outcomes described in the next section.

Pillars	Description
Food for people	People have the right to healthy and culturally appropriate Food
Values for providers	The aspirations, needs, and livelihood of those who produce, distribute, and consume Food are placed at the heart of food systems and policies
Localized Food	Local food production and consumption are prioritized in localized food systems
Local food control	Local food production has a level of control over the resources needed to produce, while communities and people govern localized food systems
Building knowledge and skills	Knowledge is spread through farmer knowledge networks on a peer-to-peer basis.
Agroecology	Agroecology is endorsed for its sustainable methods in producing Food and its benefits to communities and the environment

Table 9 Food Sovereignty's Pillars

Source: Dekeyser et al. (2018)

10 Systems' Outcomes

From an anthropocentric perspective, Food and nutritional security have been the global agri-food system's primary outcome. However, in recent years it has been questioned whether it is the only desirable outcome, since the agri-food system is strongly interconnected with many more sustainability dimensions. This is the case, for example, of climate change and biodiversity loss under the environmental dimension or inequality and well-being under the social one (Oteros-Rozas & Ruiz-Almeida et al., 2019).

Notwithstanding the broad scope of potential outcomes, Food, and nutritional security remains the most widely used concept for international organizations. It constitutes a technical concept to evaluate problems related to physical and economic access to Food at both national and regional scales. As defined in the World Food Summit of 1996, food security is reached whenever: "*every person has at every moment physical and economic access to enough nutritious food to satisfy their food consumption necessities as well as their fundamental preferences and thus be able to carry out a healthy and active life*."

During the past century, human society has remained facing relevant problems related to food insecurity. This matter forced a paradigm change to incorporate different social causes (like political instability or marginalization) as underlying conditions to reach food security (Devereux, 2000). Furthermore, some scholars have recognized the need to include an environmental analysis as an integral part of food security (Patel, 2009). La Via Campesina[12] considers food sovereignty, considering it as a pre-requisite to achieving genuine food security.

Environmental Resilience

Environmental resilience is both an outcome and a precondition for building sustainable agri-food systems (Jacobi et al., 2018). We understand it as an adaptative capacity of the ecosystems, i.e., their ability to respond to unexpected, unpredictable shocks (Holling, 2001). The environmental resilience of the ecosystems related to the agri-food systems has been measured in different ways; however, it is recognized as *a pre-requisite for agriculture to reach its urgently needed potential in contributing to multiple sustainability targets* (DeClerck et al., 2016). One of them is sustainable agriculture.

Sustainable agriculture conception emerges from the necessity to synthesize agricultural practices that differ from those that deviate from conventional production by emphasizing that the current population's feeding needs and future generations are at stake (Neher, 1992). Because this paradigm is mostly understood as a managerial philosophy, there is no explicit definition recognized. The acceptance or rejection of a particular sense is related to each person's value system (Abubakar & Attanda, 2013).

Sustainable agriculture programs often focus on environmental issues and neglect the social and economic egalitarian matters that keep them in a relatively safe political territory (Constance, 2008).

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[12] La Via Campesina is an international movement that emerged in 1993 from the union of millions of farmers, small producers, indigenous people and migrant workers. Currently it encompasses 164 local and national organizations in 73 different countries representing around 200 million peasants worldwide.

The lack of an explicit definition has caused researchers to use this term vaguely and with different connotations across scientific journals, related news, speeches, marketing campaigns, etcetera, further contributing to its ambiguity. The concept has also been adopted across a wide range of scopes, from the intensive use of fertilizers (agricultural industry) to production within organic farms.[13]

We have considered some definitions that have focused on an integral view of sustainability. The first one, proposed by Neher (1992), stated that those definitions of sustainable agriculture contain four main components: (i) environmental quality, (ii) ecologic robustness, (iii) productivity of flora and fauna, and (iv) socioeconomic viability. As an example, the author presents sustainable agriculture as a technique in which the quality of environmental and essential resources upon which agriculture relies is enhanced; one that provides critical food and fiber needs; one that is economically viable and improves the quality of life for farmers and society in general (Abubakar & Attanda, 2013).

This first definition of sustainable agriculture allows for a wide range of interpretations and uses. For instance, it will enable the new green revolution to be part of the sustainable movement, with the so-called "sustainable intensification," which presents simplistic solutions for complex problems. Due to the vagueness in its definition, Sustainable agricultures have felt short in comprising a holistic manner to understand environmental resilience.

The second definition stated that sustainable agriculture is the ability of an agroecosystem to maintain its production in time from a systemic perspective (Altieri, 1987; Neher, 1992), in which every interacting subsystem is affected or is prone to affect other subsystems. This vision is closer to a holistic view, as is the farming systems research aimed at understanding partnerships, among different stakeholders (peasants, scientists, farmers, and technicians), through realistic models that show increasingly complex relationships (Norman, 2002). Here we focus on this second definition as it tries to adapt to the complexity of the systems. We follow the agroecological approach to build sustainable food systems

Agroecology applies all the ecological concepts and principles to the design and management of sustainable agroecosystems (Gliessman et al., 1998)

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[13] The founder of “organic agriculture”, the American agricultural scientist Frankling Hiram King (1848-1911), visualizes a farm as a sustainable unit, ecologically stable and self-contained.

Agroecology endorses food productions with techniques that benefit at the same time the communities and the environment. Gliessman (2002) defines agroecology as the "*guiding light in the field of sustainable agriculture*" since it seeks to meet the nutritional needs of the population at the same time that conserves and restores natural resources in which agriculture depends on (e.g., soil, seeds, water). Agroecology also links social equity to agri-food systems sustainability. An analysis of the interrelatedness of agroecosystems components – ecological, social, and economic – is key to building greater self-sufficiency and sustainability into these food systems (Altieri and Nicholls, 2005).

The agroecology concept encompasses the study of agroecosystems[14]by focusing on the form, dynamics, and functions of all elements, interrelations, and processes in which they are involved.[15] Traditional agriculture provided a cultural and ecological base for its further development as a science (Altieri & Nicholls, 2005; Gliessman, 2014).

Like the case of sustainable agriculture, different versions have emerged for the concept of agroecology. The first one attempts to appoint agroecology into the new green revolution[16], arguing that the framework has also motivated thinking about agroecosystems at higher levels and around sustainable intensification (Foran et al., 2014; Pretty et al., 2011; Tomich et al., 2011). The second one centers on agroecology within a politically transformative peasant movement for Food Sovereignty. Holt-Giménez and Altieri (2012) argue that the livelihoods of smallholders, the elimination of hunger, the restoration of the planet's agrobiodiversity, and agroecosystem resilience would all be better served under the alliance between agroecologists and the Food Sovereignty movement scenario.

In this matter, agroecology is at the same time a scientific approach to agroecosystems' and agri-food systems' assessments, and a proposal for production technics and socio-political praxis around the ecological administration of natural resources (Calle Collado et al., 2011). Agroecology is one of food sovereignty's components regarding to the production of Food, also linked to the availability and access dimensions of FNS, and the agrarian and environmental question of Constance et al. (2014).

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[14] Agroecosystems includes both the environmental and the human elements in their study.

[15] Source: http://www.agroecology.org/

[16] The so called "Green Revolution" is the set of agricultural practices that are intensive in chemical inputs (fertilizers and pesticides) that increased agricultural production worldwide. These practices became popular between 1950s and the late 1960s

11 Social-Political Well-Being

The relationships between people and Food take many forms—the various ways we have of relating to Food directly impact the dynamics of the agri-food systems. The socio-political component of the agri-food systems' outcomes tackles such relationships according to the scale and the context subject to analysis. Thus, it cannot be left aside when analyzing agri-food systems.

As stated before, when analyzing food security as the unique outcome or the agri-food system, the social control of the systems, particularly control of the means of production and resources, is not directly considered. Therefore, reaching Food Security does not necessarily mean achieving social well-being. The latter is the main argument of finding Food Sovereignty a precondition to genuinely achieve food security (La Via Campesina, 1996).

Food Sovereignty "arises from the need to democratize production and consumption" to redistribute power relations along the food chain (Calle Collado, Soler Montiel, and Rivera-Ferre, 2010). It results from a collective effort of specific civil society organizations (CSOs), non-governmental organizations (NGOs), and social movements to carry out an international debate around the agri-food systems. The discussions contemplated a range of topics, from production problems to social concerns regarding the agri-food system. The concept of Food Sovereignty appeared for the first time in April 1996 at the International Conference of La Via Campesina in Tlaxcala, México (La Via Campesina, 2007).

This concept has evolved as new actors take relevance of the scale of analysis and support the proposal. Since its appearance in 1996, there has always been only one standing definition (i.e., more than one explanation has never coexisted at the same time). Currently, Food Sovereignty is *"the right of peoples to healthy and culturally appropriate food produced through ecologically sound and sustainable methods, and their right to define their food and agriculture systems"* (Declaration of Nyéléni, 2007)[17].

Food Sovereignty recognizes that people worldwide must have access to safe nutrition and culturally appropriate Food and the necessary resources and mechanisms for its production and consumption to support people and their societies. The essence of the concept is that to achieve Food and nutrition security, we require: (i) direct democratic participation; (ii) eradicate the usage of Food as an

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[17] Source: http://www.nyeleni.org/spip.php?page=forum&lang=en

economic weapon; (iii) a comprehensive agrarian reform, and (iv) respect for life, seed, and land (Patel, 2009). In this sense, Food Sovereignty adopts a systemic approach that includes the environmental sustainability of production and consumption methods.

12 From processing data to building the framework

Ruiz-Almeida and Rivera-Ferre (2019) covered the first five phases of Jabareen's methodology to conceptualize a concept by integrating a database of 97 indicators distributed among six categories (). These categories are subdivided according to the objective of each one of them. In their work, the authors recognize the lack of indicators on a global scale to fill each subcategory; however, representativeness is guaranteed in most of them.

Category *Objective*	Subcategories Total	Subcategories Empty	Indicators
1 Access to Resources *To support community control over resources (e.g., land, seeds, credit) respecting the indigenous communities' rights.*	8	0	20
2 Production Models *To diversify domestic production models, recovering, validating, and divulging traditional models of agricultural production.*	8	1	29
3 Commercialization *To promote local markets and to reduce intermediaries at a global scale to promote local consumption.*	6	3	12
4 Food Security and Food Consumption *To protects communities' right to Food and Food security*	6	1	9
5 Agrarian Policies and Civil Society Organization *To protect peasants, farmers, and food producers' right to know, participate and influence over local public policy*	7	2	20
6 Gender *To promote gender equality in each category.*	5	2	7

Table 10 Distribution of indicators among food sovereignty categories and subcategories
Source: Adapted from Ruiz-Almeida & Rivera-Ferre (2019)

In their work, the authors claim that food sovereignty offers a political framework to develop sustainable agri-food systems. Despite the growing acceptance of this concept as a robust and viable alternative to reach "zero hunger," promote rural development and mitigate the environmental crisis

(Oteros-Rozas et al., 2019), they do not find enough quantitative studies to analyze the proposal's efficiency in achieving such objectives.

In this work, we go further basing on Ruiz-Almeida and Rivera-Ferre's work. We analyze the indicators' interconnection by synthesizing the concept into a theoretical framework and rethinking it as a dynamic phenomenon. Such interconnections dynamically change according to the context (e.g., new insights, research, view, and diets) and scales.

13 Synthetizing concepts into a theoretical framework

We can summarize that the primary agri-food system's outcomes are: Food and nutritional security, environmental resilience, and socio-political well-being; all of them linked by a transversal outcome: stability. Therefore, a sustainable agri-food system is such that the three primary outcomes are reached through time. The systems' internal dynamics must rely on a permanent assumption that the interactions occur under a societal justice and gender equality lens (emancipatory question).

Methodology

We use an innovative approach coming from the complex networks science framework (Newman, 2009). Although complementary, this methodology departs from the same data used in Otero-Rozas, Ruiz-Almeida et al. (2019). The authors debug the original database to 1) minimize the repetition of information in different indicators, 2) reduce extrapolation of data as much as possible, and 3) avoid outliers due to country or population size, reducing it to 45 indicators. These 45 indicators, coming from 150 countries were normalized (i.e., mean=0, standard deviation = 1) and rescaled using the max-min process to show values between 0 and 1.

In this approach, we follow three consecutive steps. We firstly use countries and normalized indicators as groups and vertices, respectively, to construct a bipartite graph.[18] Indicators are used as weights for our second step: the construction of the two possible projections that can be obtained from this type of graph:

(a) Countries onto indicators, to obtain a unipartite graph where only countries are present. Here, two countries are connected by a weighted link, with this weight being the result of the vectorial product of the different indicators for those two countries. In this sense, the

[18] For more reference see https://en.wikipedia.org/wiki/Bipartite_graph

more the weight, the stronger the connection (i.e., stronger similarity) between both countries.

(b) Indicators onto countries, to obtain a unipartite graph where only indicators are present. Here, two indicators are connected by a weighted link, with this weight being the result of the different countries' vectorial product for those two indicators. In this sense, the more the weight, the stronger the connection (i.e., stronger similarity) between both indicators.

The final step is applying modularity algorithms to both networks to detect communities (also called clusters, modules, or groups) of countries and indicators (Clauset et al., 2004; Wakita & Tsurumi, 2007). Since networks with high modularity have dense connections between the nodes within modules but sparse connections between nodes in different modules, the objective is to detect how potential decisions or policies applied to a group's elements can affect the other group members' dense connectivity among them.

First Results

Although this study's scope is to analyze the relationship among indicators that provide a visual conceptualization of the agri-food system's sustainability, we run the methodology to analyze both projections..

Firstly, the country onto indicators analysis in which out of a total of 11175 connections, only 1091 most substantial remain as a part of the analysis. That selection involves 109 countries (72% of the originals). shows the preliminary results, where the size of the node corresponds to its degree centrality (i.e., the number of connections this node has).

Using Wakita and Tsurumi's (2007) modularity algorithm, we obtain eight groups, with two consistent on individual countries. It is not within the objectives of this chapter to study the behavior of countries as communities, it will be the next chapter’s objetive. However, from this analysis, we can highlight that among the resulting groups, Group 2 is formed only by the developed countries, the United States, Canada, and the European Union, which stands out that those countries have a similar level in terms of indices.

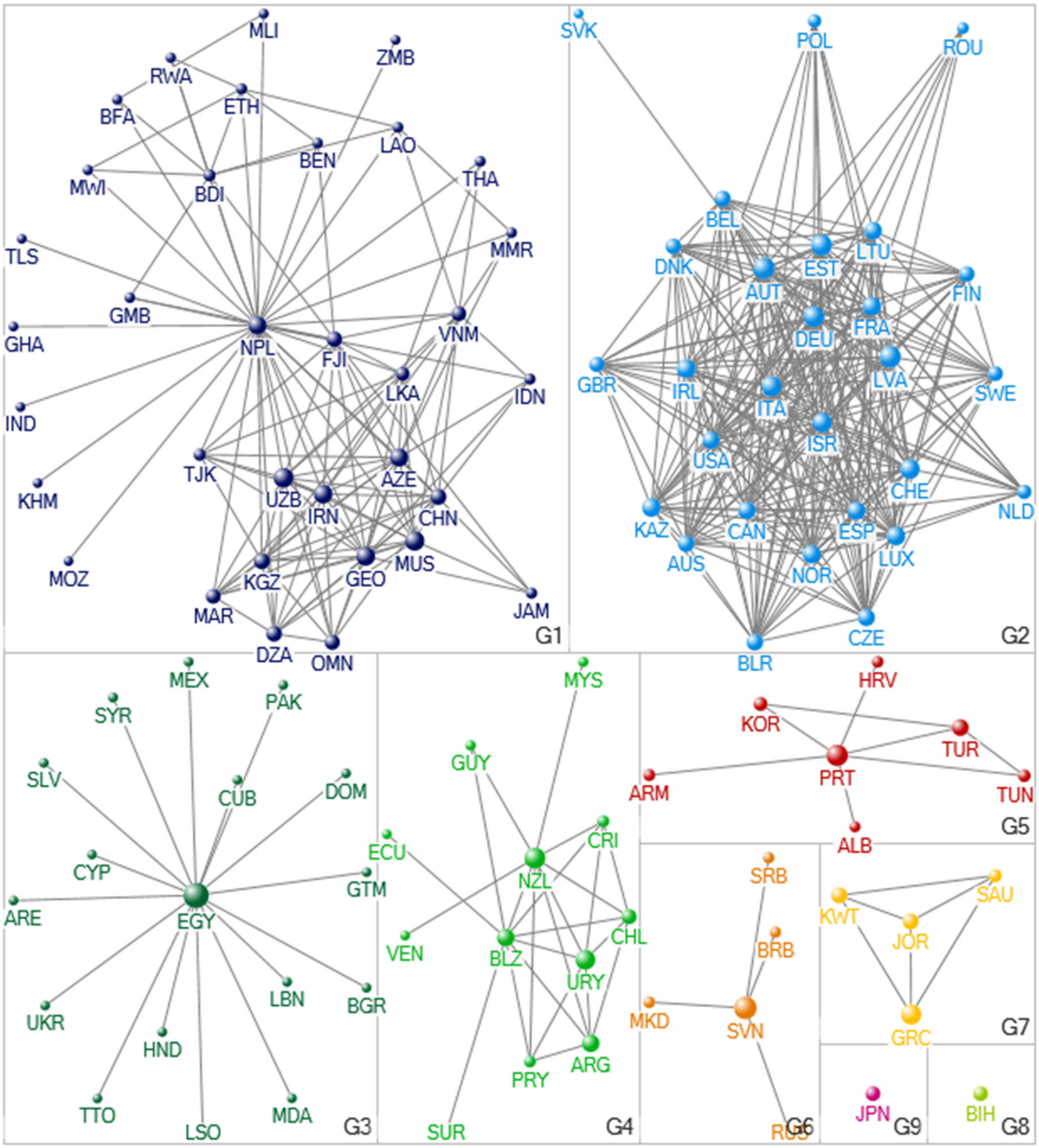

Figure 10 Projecting countries onto indicators give rise to a unipartite graph with only countries as vertices.
Source: Prepared by the authors using NodeXL (http://nodexl.codeplex.com)

Second, the indicators onto countries graph () shows the communities set by 519 of the heaviest connection out of 990 initial connections. This analysis implies 44 indicators (97% of the originals).

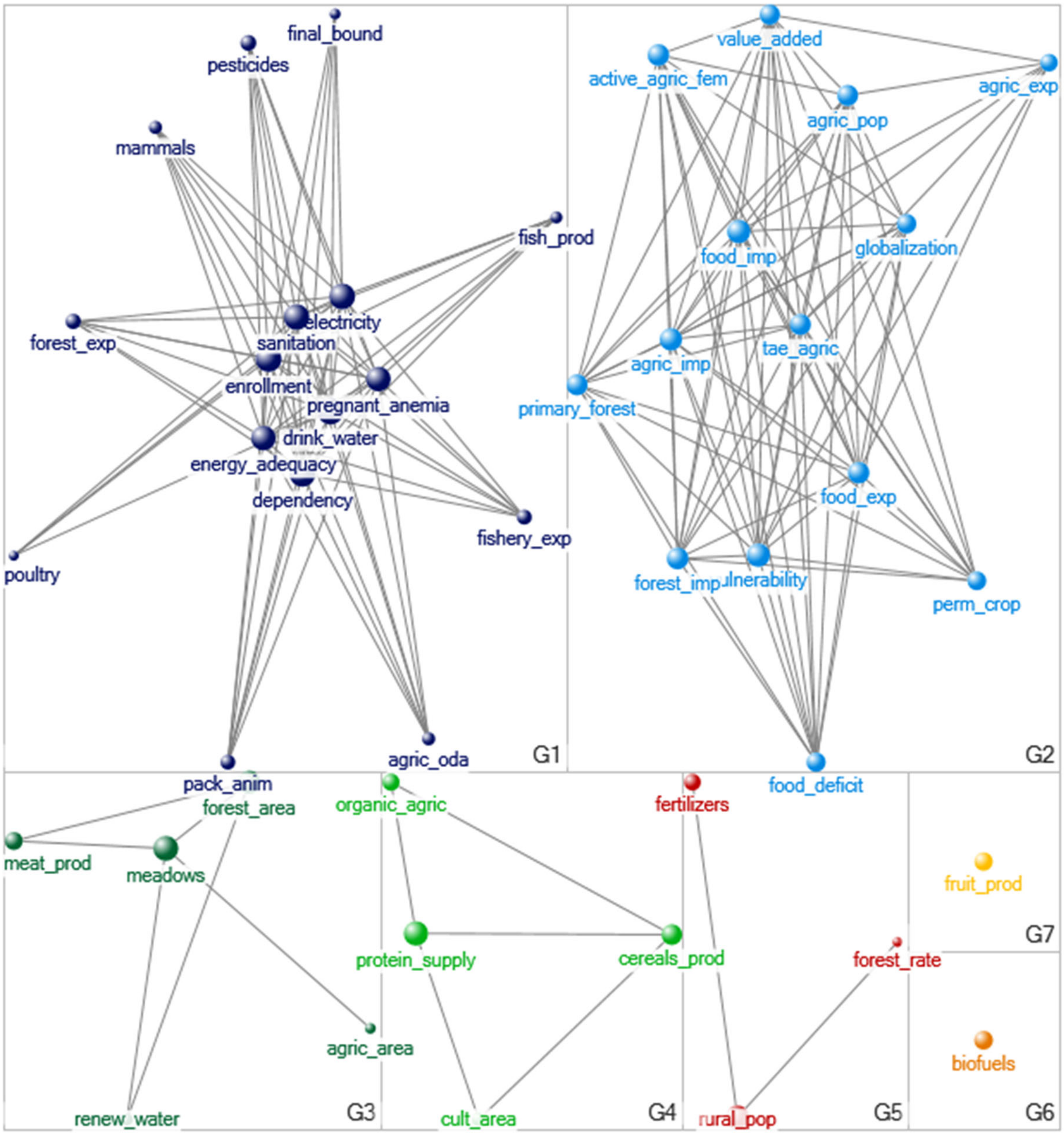

Figure 11 Projecting indicators onto countries give rise to a unipartite graph with only indicators as vertices.
Source: Prepared by the authors using NodeXL (http://nodexl.codeplex.com)

Again, using Wakita and Tsurumi's (2007) modularity algorithm, we obtain seven groups. The size of the nodes corresponds to its degree centrality (i.e., the number of edges that connect it to other indicators). From this graph, we can make the following preliminary remarks, although further study is needed to understand the results better.

- The first biggest group in terms of indicators (G1) contain indicators related to all of the six food sovereignty pillars. Therefore, we need to go further in the analysis to determine which strengthens the interactions since it seems to be relating dependency of food anemia with access to resources (natural, economic and infrastructure resources).
- The second biggest group (G2) suggests a relation with the international position (i.e., global trade) with some of the main population characteristics and food vulnerability.
- Groups G3 and G4 highlights the production of meat and cereals, respectively.
- Group G5 relates the rural population with the uses of chemical inputs and deforestation.
- Finally, groups G6 and G7 are single-indicators groups.

We expect to analyze in detail our results in the near term to be able to suggest possible explanations to the relations between indicators and within each group.

14 Next steps

Final phases of Jabareen's methodology establish the need to clarify the interactions among the different concepts around the agri-food system's sustainability and the need to validate the conceptual framework. The latter point will be analyzed in the next chapter, but for now let's keep in mind that a "*theory of a theoretical framework representing a multidisciplinary phenomenon will always be dynamic and may be revised according to new insights, comments, literature, and so on. As the framework is multidisciplinary, the theory should make sense for those disciplines and enlarge their theoretical perspective on the specific phenomenon in question"*.

By definition, the agri-food system is a dynamic complex system that will be continuously updated concerning consumption preferences, food allocation, and food production. Therefore, the last phase, Phase 8 Rethinking the conceptual framework, takes a significant relevance in this assessment's continuity.

Here we present a set of indicators around the concept of food sovereignty as the "complete framework" to measure sustainability. It is the closest framework to build a sustainable and resilient agri-food system. Food sovereignty is often described as a political framework that focuses on the food system's outcomes: food security, stability, ecosystem resilience, and socio-political well-being.

This work continues, thus any result herby presented is a preliminary assumption and will not be necessary hold in the publication.

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Chapter 3. A social-ecological analysis of the global agri-food system: Insights for advancing SDG2

Abstract

The failure to eradicate world hunger – the aim of Sustainable Development Goal 2 – emphasizes the need for a social-ecological approach to agri-food systems. An analysis of agri-food systems from the perspective of sustainability sciences can inform the path towards this goal. Through a quantitative multivariate assessment of 43 indicators of food sovereignty and 39 indicators of socio-demographic and social wellbeing and environmental sustainability in 150 countries, we depict the global food panorama. The results indicate an agri-food debt, i.e., disequilibria in the natural resources consumed, the environmental impacts produced, and the social wellbeing attained by populations in regions that play different roles within the globalized agri-food system. Three spotlights underpin this debt: (a) a severe contrast in diets, and food security between regions; (b) concern about the role international agri-food trade is playing in regional food security; and (c) a mismatch between regional biocapacity and food security. Our results contribute to broadening the debate beyond food security from a social-ecological perspective, incorporating environmental and social dimensions.

Significance Statement: *The failure to end hunger and the environmental deterioration underpinning food systems has prompted a paradigm shift around food security. We propose a social-ecological approach and carry out a quantitative analysis of 43 indicators of food sovereignty and 39 indicators of the socio-demographic, social wellbeing, and environmental sustainability situation in 150 countries. The results highlight the existence of an agri-food debt among countries, i.e., disequilibria in the natural resources consumed, the environmental impacts, and the social wellbeing in regions that play different roles within the globalized agri-food system. Three spotlights underpin this debt: (a) inter-regional contrasts in food security; (b) concern about the role of agri-food trade; and (c) a mismatch between regional biocapacity and food security.*

1 Introduction

Agri-food systems, given their place among the most vulnerable coupled nature-human systems (Porter et al., 2014; Rivera-Ferre, Ortega-Cerdà, et al., 2013), have multiple interactions with global environmental change and play a major role in the present and future of humanity (Bennett, 2017; Raudsepp-Hearne et al., 2010). They contemporarily sustain and challenge social wellbeing and human life on the planet (Bennett, 2017) by providing food while contributing to global greenhouse gas emissions, land degradation, eutrophication, and water quality depletion (J. A. Foley et al., 2011; Smith et al., 2014; West et al., 2014a). Five of the seven planetary boundaries are directly linked to agri-food systems (Rockström et al., 2009; Steffen, Richardson, Rockström, Cornell, Fetzer, Bennett, Biggs, Carpenter, de Vries, et al., 2015). However, in a context in which enough calories are produced to feed the entire human population (Chappell & LaValle, 2011), chronic hunger still affects one in nine people in the world (FAO, 2017b). The evident failure of policies to end hunger and the environmental deterioration underpinning agri-food systems has prompted a paradigm shift in the way food security is approached, both scientifically and in policy terms: from being mostly focused on the technical and agrarian aspects of food production (J. A. Foley et al., 2011; Godfray et al., 2010; Porter et al., 2014; Tester & Langridge, 2010) to adopting a social-ecological systems approach (Schipanski et al., 2016) and, more precisely, an agri-food system approach, including both environmental sustainability and social wellbeing (Bennett, 2017; Chaudhary et al., 2018; Ericksen, 2008; Loos et al., 2014; Schipanski et al., 2016; Vallejo-Rojas et al., 2016; West et al., 2014a, 2014b). This systemic perspective allows emphasis on the use of natural resources for primary production, as well as food transformation, commercialization and consumption, therefore connecting pieces within agri-food systems that previous analyses had studied separately.

Likewise, the multiple social and ecological dimensions of food security are transversal to 14 out of the 17 United Nations' 2030 Sustainable Development Goals (SDGs) (UN, 2016). The SDGs aim to eradicate poverty, establish socioeconomic inclusion and protect the environment (Swain, 2018), so the need for an integrative approach to address them has already been discussed (Lim et al., 2018). However, critical studies have elicited an incompatibility between the environmental, social, and economic aspirations of the SDGs (Spaiser et al., 2017).

While food security is commonly defined as the physical, social, and economic ability to access sufficient, safe, and nutritious food (FAO, 1996), SDG2 implicitly recognizes that a broader approach to food security is needed to end hunger. Indeed, for the first time, the SDG2 links the objectives of zero hunger, food security, and improved nutrition (subgoal 1) with the need to promote sustainable agriculture (subgoal 2; 20). It explicitly contributes to the global moral imperative to eradicate hunger while respecting environmental sustainability. However, this entails controversy about the trade-offs between achieving food security mainly through increasing food production (Hunter et al., 2017; Tilman et al., 2011), addressing and minimizing the environmental impacts of agriculture and food (West et al., 2014a) and adapting to climate change (Vermeulen et al., 2012). Therefore, actions towards the transformation of agri-food systems need to account for the synergies and trade-offs that exist between SDG2 and other SDGs (Campbell et al., 2018).

The international debate around the social-ecological sustainability of food systems is prolific, and different authors have recently suggested a change from the land-sparing/sharing debate to a focus on human wellbeing (Bennett, 2017); proposed “leverage points” for improving global food security and environmental sustainability (West et al., 2014a); argued for sustainable healthy diets to keep food systems within the planetary boundaries (Willett et al., 2019a); developed assessments of the environmental impacts of food systems (Poore & Nemecek, 2018; Springmann et al., 2016); applied metrics for the assessment of the sustainable nutrition outcomes of food systems (Gustafson et al., 2016); and provided a valuable systemic analysis of global food systems (Chaudhary et al., 2018). However, although it is widely acknowledged that the social and environmental costs and benefits associated with environmental change are not distributed equally among actors and regions (Nilsson et al., 2018), how this phenomenon occurs is still poorly understood because less than 6% of food security publications in the past 25 years included equity or justice as part of their analysis (Schipanski et al., 2016).

A tipping point in these international debates was the 2012 Thirty-Second Regional Conference for Latin America and the Caribbean (FAO, 2012), where the United Nations Organization for Food and Agriculture (FAO) agreed to initiate discussions about alternative approaches to address hunger and the unsustainability of agri-food systems. One such approach was Food Sovereignty (FAO, 2012). Food Sovereignty emerged in the late 1990s, arguing that hunger is not merely a matter of food availability and quality but that equally or more critical issues are political aspects harnessing equity and justice within food systems. Those may include agricultural trade liberalization, power relations between different actors (from small producers to large transnational corporations and consumers), a lack of wide social participation along the whole food chain, or access to the means of production (Claeys, 2015a; Levidow et al., 2014). Food Sovereignty was coined by La Via Campesina, an international movement of farmers, peasants, and landless workers, and has been developed and discussed at large by civil society organizations, farmers' trade unions, academia, governments, and international institutions (De Schutter, 2014) to become a well-rooted concept (Patel, 2009). Within this approach, food is framed as a human right, including its environmental and socio-cultural aspects, which are viewed as both drivers and outcomes of food security and where small farmers are considered to play a central role (Claeys, 2015a).

However, progress towards ending hunger needs to be measurable through indicators that aid societies in assessing their performance (Swain, 2018). (Ruiz-Almeida & Rivera-Ferre, 2019)proposed Food Sovereignty as a conceptual framework to analyze the food system's sustainability and its capacity to tackle hunger at the international level. They proposed a panel of 97 indicators that are classified into six pillars explaining food systems from a food sovereignty perspective: (a) access to resources, (b) production model, (c) commercialization, (d) food consumption and right to food, (e) agri-food policies and civil society organization and (f) gender. Based on this set of indicators, we analyze here the global agri-food system from a social-ecological sustainability perspective in order to quantitatively assess at the international level the role that different countries play within the system and the links with social wellbeing and environmental sustainability.

To do this, we carried out a Principal Component Analysis (PCA) of 43 indicators (variables) describing the agri-food system (Tables SM.3 to SM.7) in 150 countries (observations). Using the standardized coordinates of the most significant PCA factors, we performed a Hierarchical Cluster Analysis (HCA) based on the Euclidean distance and Ward's agglomerative method. Finally, we used Kruskal-Wallis and Chi2 tests to characterize each cluster of countries according to its performance in terms of Food Sovereignty, seven demographic and economic indicators, five social wellbeing indicators, and 17 environmental sustainability indicators (a more detailed description of statistical methods and results can be found in the Supplementary Materials). This approach aims to contribute to other ongoing efforts to provide indicators for monitoring SDG progress (see http://indicators.report).

In analyzing the relationship between Food Sovereignty, social wellbeing, and environmental sustainability, we (a) identify world regions formed by countries under similar conditions of Food Sovereignty; (b) relate the state of Food Sovereignty of the different regions with their state of social wellbeing and environmental sustainability; and (c) critically reflect on the implications for SDG2 of an agri-food debt between world regions that have been so far poorly addressed.

2 Results

The state of food sovereignty: who is who in the global agri-food system

The 150 countries analyzed were statistically clustered into five groups (Table S8 and Fig. 1) according to their performance in the 43 indicators across the six pillars of Food Sovereignty (Figs. 1 and 2). By also characterizing them according to their bioregional context (Table S10), socioeconomic characteristics (Table S11), Food Sovereignty (Table S12), environmental sustainability, and social wellbeing (Table S13), we grasp who is in the global food system and what relationship with the ecological and socio-political dimensions of food the different groups of countries have.

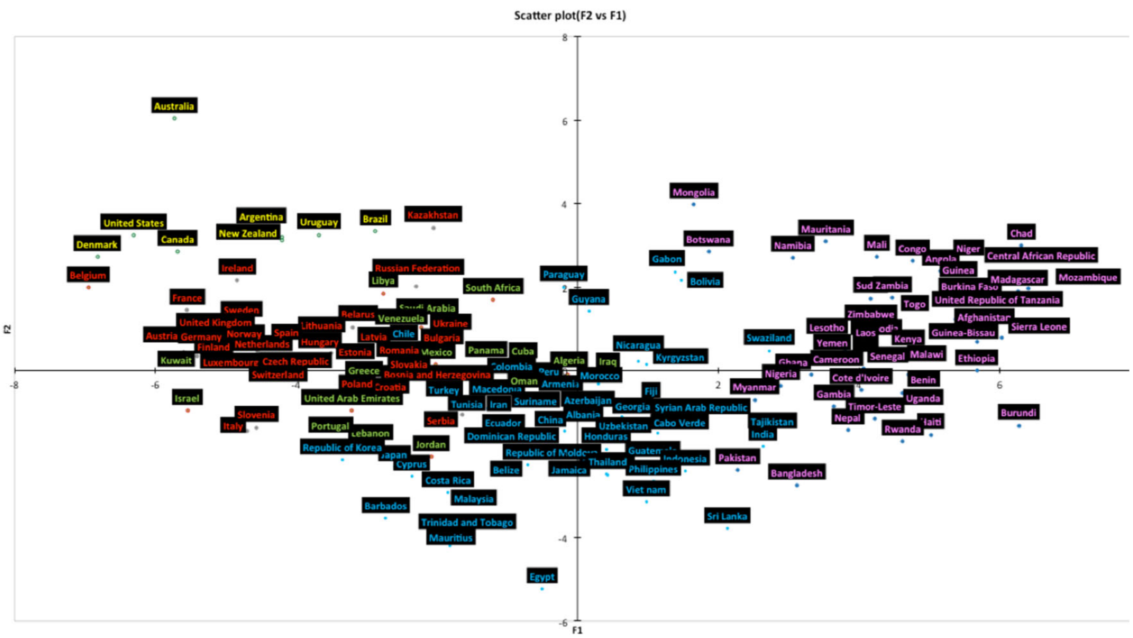

Fig. 1a. Scatter plot of the countries in the first and second axes of the principal component analysis.

Labels in the scatter plot and countries on the map are colored according to the groups from the principal component analysis and the hierarchical cluster analysis:

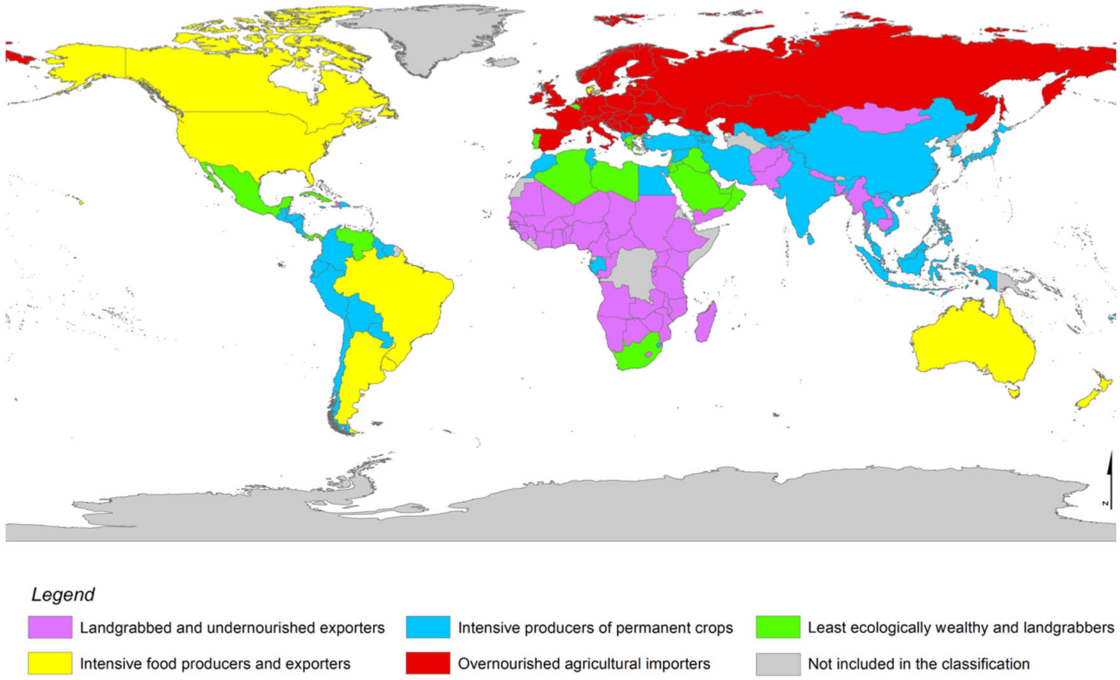

Fig. 1b. World map.

In purple is group 1, blue is group 2, green is group 3, yellow is group 4, red is group 5, and grey indicates the countries excluded from the analysis due to a lack of data.

1. Landgrabbed and undernourished exporters

The first group includes 45 countries (Table S9 and Fig. S4), mostly from Eastern, Middle, and Western Africa (Table S10, Fig. 1). The countries in this group show the lowest GDP per capita and very low income (Table S10). The food systems in the countries of this group are characterized by a productive model based on the largest rural and agricultural population of the sample, the smallest cultivated area per farmer, the largest total economically active population in agriculture, limited use of fertilizers, and low production of meat (Table S12, Fig. 2). Agriculture is responsible for a high share of the GDP of these countries, which are, on the one hand, the largest exporters of agricultural products and, on the other hand, the largest importers of food, showing net reception of official development assistance for food and agriculture (Table S12). This group of countries ranks first in suffered land grabbing (Table S11). The population in the countries of this group shows the lowest levels of access to resources such as electricity, sanitation, and drinking water, the most severe food deficits, and significant vulnerability, which is consistent with the lowest protein supply and adequacy of the dietary energy supply among the groups (Table S12, Fig. 2). That is, the value-added of the agricultural products produced is not retained, exporting huge amounts of agricultural products while failing to feed large shares of their population. These countries also show the lowest degree of globalization. The indicators of social wellbeing are coherent with the former, as this group of countries has the worst scores for all the indicators analyzed, including significantly shortest life expectancy and worse life satisfaction (Table S13, Fig. 3). In terms of environmental sustainability, these countries are associated with the lowest ecological footprint and low CO_2 emissions, and water withdrawal from agriculture (Table S13, Fig. 3).

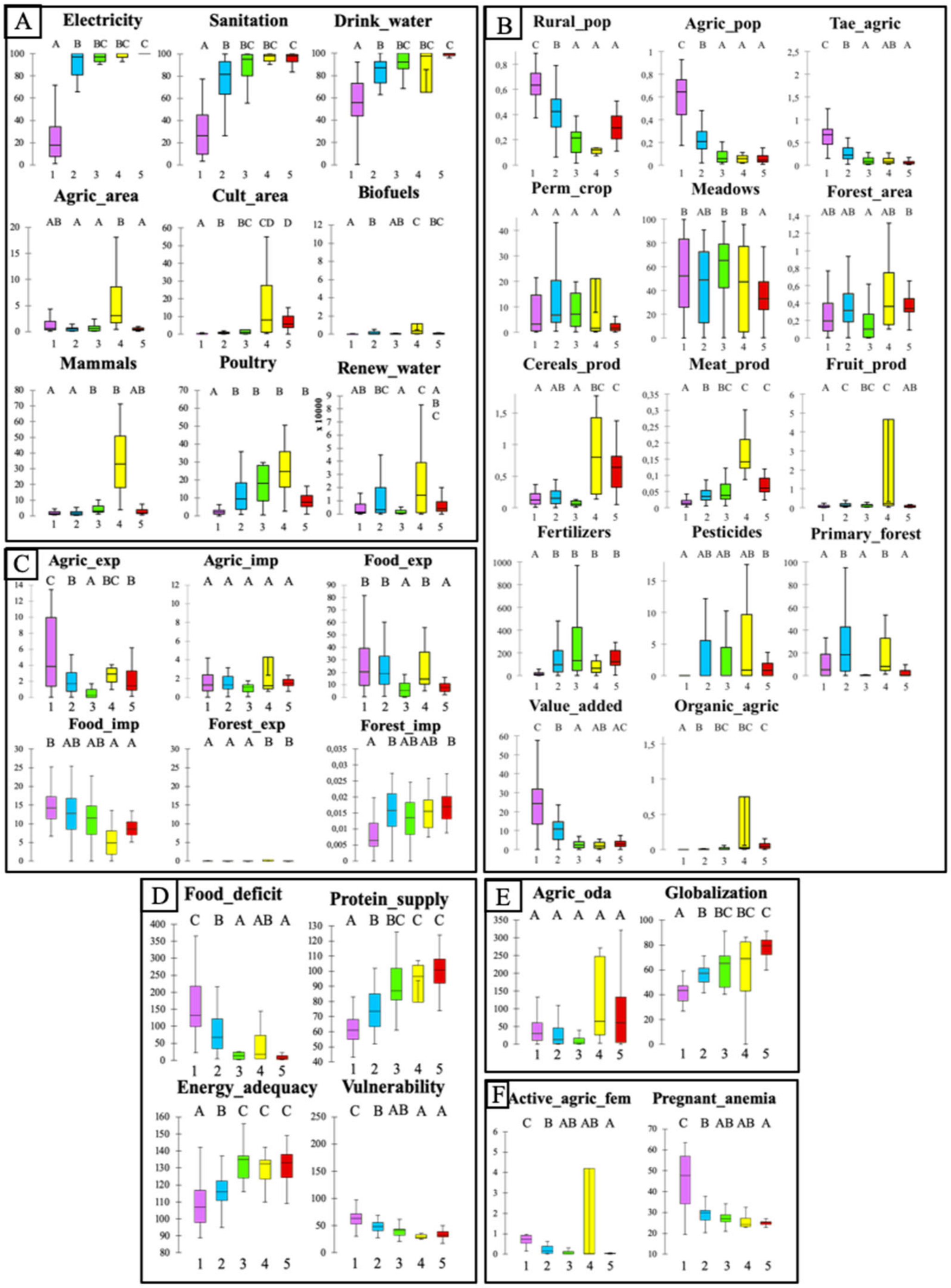

Fig. 2. *Box plots of food sovereignty indicators in the 5 clusters identified.*

Only indicators with statistically significant differences between the groups are represented. The six pillars of food sovereignty are separated in A) Access to Resources; B) Productive Models; C) Commercialization; D) Food Security and Food Consumption; E) Agrarian Policies and Civil Society Organizations; F) Gender. The letters at the top of each box plot (A, B, C, D, and combinations) correspond to the statistically significant differences in the pair comparisons (for more details, see the Supplementary Information).

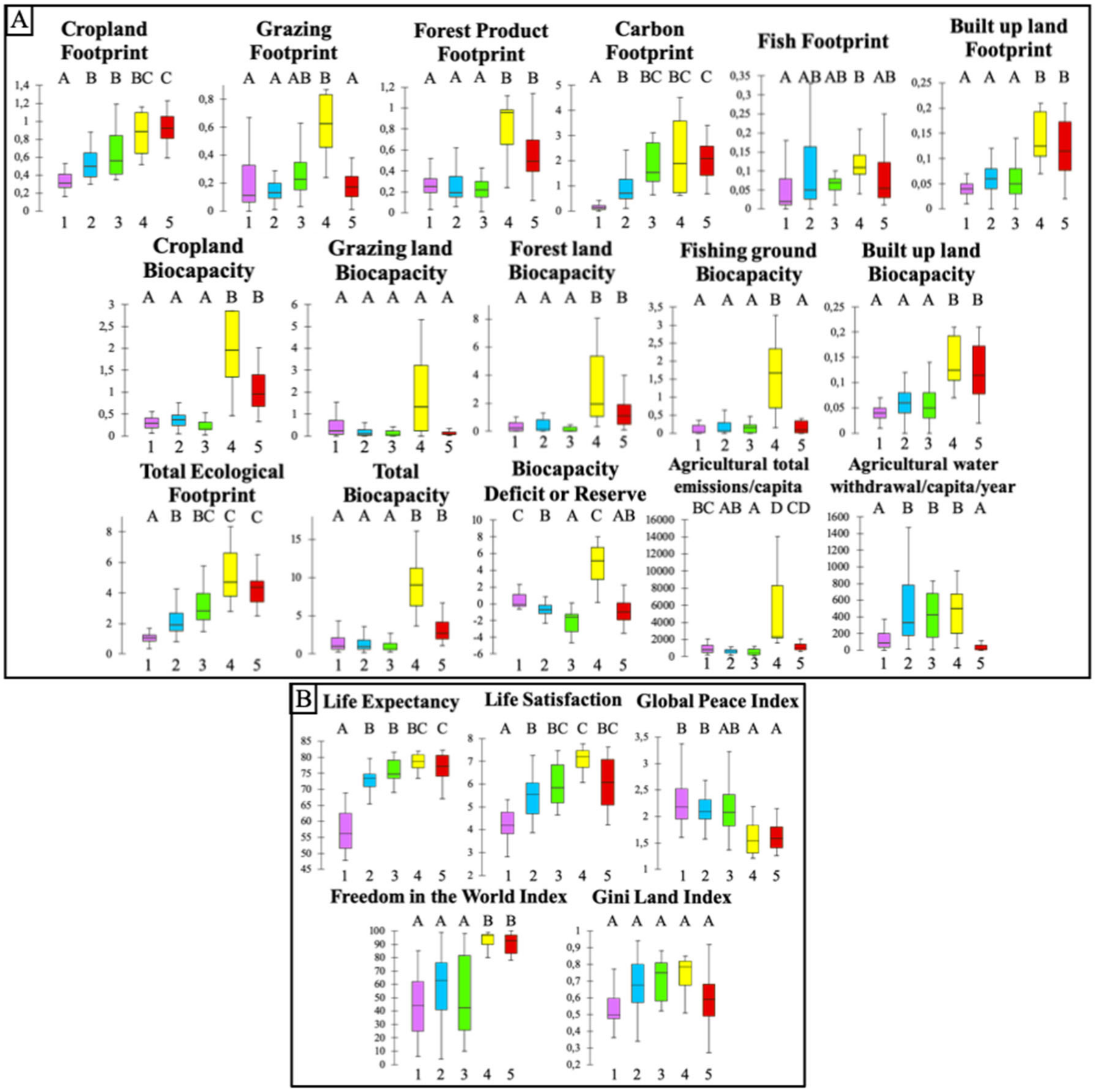

Fig. 3. Box plots of environmental sustainability (A) and social wellbeing (B) indicators in the 5 clusters identified.

The letters in the top of each box plot (A, B, C, D and combinations) correspond to the statistically significant differences in the pair comparisons (for more details, see the Supplementary Information).

2. Intensive producers of permanent crops

The second class is the largest and most heterogeneous group, clustering together 49 countries (Table S9), mostly from Asia and the Americas (Table S10, Fig. 1). In comparison to the other groups, these countries have the largest population densities and low-medium income (Table S11). These countries show medium levels of rural and agricultural populations; however, with the smallest agricultural area and production of mammals (Table S12, Fig. 2). They are characterized instead by the vastest surfaces of permanent crops that are dedicated partly to fruit production and involve a strong use of fertilizers and agricultural water withdrawal, which is potentially related to their large food exports (Table S12, Figs. 2 and 3). Countries in this group are also characterized by the second-highest food deficit, low energy and protein intake (Table S12, Fig. 2), and overall intermediate levels of social wellbeing (Table S13, Fig. 3).

3 Least ecologically wealthy and landgrabbers

The 18 countries clustered in this class are not geographically or eco-regionally grouped (Tables S9 and S10, Fig. 1). They show medium population densities and GDP per capita (Table S11). Countries in this group show a limited proportion of agricultural area and forests, as well as overall very little cereal, meat, and fruit production but the greatest use of fertilizers (Table S12, Fig. 2). Little of the population lives in rural areas or is dedicated to agriculture, and overall, the population in these countries seems to have good access to all resources except renewable water (the group includes several island states) (Table S12, Fig. 2). These countries have limited exports of agricultural products, and they are net food importers, with limited value added to agriculture (Table S12, Fig. 2). Most of these countries coincide with those in which the importance of food imports has increased in recent years. They show an intermediate level of food security and consumption in comparison to the other groups, in spite of limited subsidies invested in supporting agriculture (Table S12). Overall, they seem to have a good situation in terms of social wellbeing (Table S13, Fig. 3). Two significant characteristics of this group are the largest biocapacity deficit in comparison to the other four groups (Table S13, Fig. 3) and the largest area of land grabbed abroad (Table S11).

4 Intensive food producers and exporters

The fourth group clusters eight vast countries from Oceania and the Americas with the largest intra-group variance (Tables S9 and S10, Fig. 1). This group exhibits high income and the largest GDP per capita alongside the smallest population densities (Table S11). Access to resources is high in these countries, and the agri-food system is focused largely on a model of intensive production of cereals, fruit, meat, and biofuels, dependent on large inputs of pesticides and with very low rural and agricultural populations (Table S11, Fig. 2). However, organic agriculture scores high in this group due to Uruguay and the United States. Countries in this group appear to be the "breadbasket of the world": they show a large share of food and agricultural exports while indicating limited food imports (Table S12, Fig. 2). In fact, some of them, such as Australia, Argentina, Canada, the United States, and, most recently, Brazil, dominate global food exports. This group also shows the largest financial support for agriculture (Table S12, Fig. 2). Food deficit is quite low and the protein supply is high, consistent with the high level of energy adequacy (Table S12, Fig. 2). Another common feature of countries in this group is their large ecological footprints and agricultural CO_2 emissions, as well as a large biocapacity that sustains their large biocapacity reserves (Table S13, Fig. 3). Furthermore, they have the best records for all social wellbeing indexes (Table S11, Fig. 3).

5 Overnourished agricultural importers

The fifth group is the most homogeneous group and includes 30 countries (Tables S9, Fig. S4), mostly in Europe (Table S10, Fig. 1), and features the largest population densities, the second largest GDP per capita, and high income (Table S11). Access to resources is satisfactory in these countries (Table S12, Fig. 2). Agriculture is quite intensified, with little and masculinized rural and agricultural populations and large use of fertilizers (Table S12, Fig. 2). These are the largest importers of agricultural products, however, with little imports and exports of food (Table S12, Fig. 2). People in these countries are overall food secure but have a diet largely based on a large consumption of proteins (Table S12, Fig. 2). These countries are in a biocapacity deficit because of the ecological footprint of the built-up land and the croplands, instead of showing the lowest grazing footprint and agricultural water withdrawal but large CO_2 agricultural emissions (Table S13, Fig. 3). These are the countries with the largest degree of globalization and net contribution of official development assistance for food and agriculture, as well as overall high levels of social wellbeing (Tables S12 and S13; Figs. 2 and 3).

3 Discussion

The Food Sovereignty indicator framework (Ruiz-Almeida & Rivera-Ferre, 2019) used here to analyze agri-food systems from a social-ecological systems perspective (Schipanski et al., 2016) contributes to systematically and quantitatively assessing environmental, social, and economic relationships between countries within a globalized world. It allows us to measure progress through periodical monitoring: ideally, countries should not be so easily clustered, and if they are, the groups should not show significant differences in terms of their socio-demographic characteristics, environmental sustainability, and social wellbeing. The current clusters might help countries to (a) be conscious of the impacts of their national agri-food policies in other countries and on their social-ecological sustainability, (b) evaluate the dependence of their food security, social wellbeing, and environmental sustainability on other countries, and therefore (c) allow governments to make sensible changes to agri-food policies to contribute to SDG2.

Winners and losers: agri-food debt

The International Council for Science critically pointed towards the internal inconsistency between ecological sustainability and socioeconomic progression in the SDG framework (ICSU & ISSC, 2015), but there is limited quantitative evidence about the nature and extent of this incompatibility of sustainability and development (ICSU & ISSC, 2015; Stern et al., 1994). Our results provide evidence of the challenges to end hunger in a globalized agri-food system, which is far from equitable from both socioeconomic and environmental perspectives. Certain countries, such as Australia, Brazil, Argentina, and those in Europe and North America, hold a critical stake and should reduce over-consumption, while other countries, such as most of Africa, would benefit from improving their self-sufficiency. Our results show that intertwined and nested material flows in global agri-food systems result in inter-regional social inequities in the distribution of both costs and benefits of producing, trading and consuming food, hence affecting social wellbeing, unevenly distributing environmental impacts and challenging environmental sustainability.

In line with the concept of "ecological debt," which was coined by academics in 1992 and further adopted and developed by civil society organizations and governments (Goeminne & Paredis, 2010), the results presented here illustrate an agri-food debt, i.e., the inter-regional social-ecological disequilibria in the natural resources consumed, the environmental impacts produced, and the social wellbeing attained by populations in regions that play different roles within the globalized agri-food system. Given that a substantial proportion of the world's 815 million people who are unable to meet daily food needs are food producers, such as small-scale farmers and fishers (FAO, 2017b), our results confirm that food security is largely a matter of redistribution, entitlements, food access, and access to services and means of production (Sen, 1981; Spaiser et al., 2017). Globalization poses complex trade-offs for food system resilience across scales due to high social, economic, and ecological interconnectedness, trade-offs, and, hence, vulnerability (Schipanski et al., 2016). We suggest that this agri-food debt, which has been poorly addressed to date, should be recognized, assessed, and monitored through three spotlights: (a) a severe contrast in diets and food security between regions; (b) concern about the role international agri-food trade is playing in regional food security, and (c) a mismatch between regional biocapacity and food security.

Nutritional and environmental contrasts in diets and food security between regions

An unbalanced food system features a contrast between high rates of under-nutrition (group 1) vs. over-nutrition (in groups 4 and 5), leading to increasing overweight and obesity (FAO, 2017b), which highlights the need to promote dietary changes in many countries of the Global North (Chaudhary et al., 2018; Dixon et al., 2007; Poore & Nemecek, 2018; Willett et al., 2019b). Divergences in diets are reflected by the differences in carbon footprints between the groups: mean dietary carbon footprints vary from ca. 0.7 kg CO_2 eq. per capita per day for certain African countries (all in group 1), to 4 kg CO_2 eq. per capita per day for New Zealand, Australia, the United States, France, Austria, Argentina and Brazil (all in groups 4 and 5) (Chaudhary et al., 2018). If current crop production used for animal feed and other non-food uses such as biofuels (particularly in the United States, China, Western Europe, and Brazil) were used for direct human consumption, ca. 70% more calories would be available, potentially satisfying the basic needs of 4 billion people (Vermeulen et al., 2012). Our results confirm that most countries with a high nutritional quality show high ecological footprints, so changes in the diets in North America (group 4) and Europe (group 5) would entail the largest reductions in environmental impacts of the global agri-food system (Bajželj et al., 2014; Berners-Lee et al., 2018b; Chaudhary et al., 2018). However, concerns about nutrient density and public health must be incorporated into considerations around the environmental impacts of food and consequently integrated into agricultural policies (Chaudhary et al., 2018; Drewnowski et al., 2015; Schipanski et al., 2016). The point at which the higher carbon footprint of some nutrient-dense foods is offset by their higher nutritional value is a priority area for additional research.

Therefore, “doubling the agricultural productivity of small-scale food producers,” as stated by SDG2, is, per se, not the way to eradicate hunger in a context where the world is already producing food to feed 12 billion people (D’Odorico et al., 2014; Ziegler, 2013). On the contrary, it might be even ecologically counterproductive unless other agri-food policies are adopted, such as the reduction of the demand-side and particularly animal-sourced food in the diets of countries in groups 4 and 5 and of some countries in group 3, the diminution of impacts of the supply chain, and the incentive of low-impact and crop-diversifying farming systems (Bajželj et al., 2014; Berners-Lee et al., 2018b; Chaudhary et al., 2018; Poore & Nemecek, 2018; Schipanski et al., 2016).

International agri-food trade, food security, and environmental sustainability

International trade plays an important role in food security (D’Odorico et al., 2014), and the promotion and maintenance of certain lifestyles and diets rich in calories has been possible thanks to the global food trade (Porkka et al., 2013); SDG2 states that "access to financial services, markets and opportunities to value addition" is needed. However, unless regulated and complemented with other policy instruments, the global agri-food trade entails trade-offs in terms of social equity and environmental sustainability (Sun et al., 2018). In fact, securing the food supply through imports occurs only in strong enough economies (Berners-Lee et al., 2018b; Porkka et al., 2013), and international agri-food trade can contribute to increasing social inequality in the form of food insecurity, with some groups of countries losing (groups 1 and 2) with respect to others (4 and 5). The first group of countries (mostly in Africa) is a clear example of this: despite their large exports of agricultural products and the largest imports of food, under-nutrition remains a critical limitation.

More than one-fifth of global calorie production is exported, mostly from countries in group 4 (the United States, Canada, Brazil, and Argentina) (MacDonald et al., 2015). Industrialized countries with high GDP per capita tend to be major net importers of biodiversity, while tropical countries such as Argentina and Brazil suffer habitat degradation and biodiversity loss as a result of producing crops for exports (Chaudhary & Kastner, 2016). Land use for export production is responsible for 25% of the projected global extinctions and related biodiversity loss (Chaudhary & Brooks, 2017; Chaudhary & Kastner, 2016), approximately 20% of global harvested cropland area is devoted to export production (MacDonald et al., 2015), and most of the new cropland expansion is globally attributed to the production of crops for export (Kastner et al., 2014). The international food trade has been related to a virtual transfer of water (Allan, 1998), carbon (Schipanski & Bennett, 2012), nitrogen (Galloway et al., 2007), and phosphorus (Kastner et al., 2011), while the environmental impacts of agricultural production tend to remain in the producing countries (Meyfroidt et al., 2013).

The mismatch between regional biocapacity and food security

There has been a strong decoupling between regional biocapacity and food consumption. The global tele-coupling (Liu et al., 2016) and increasing interdependence among countries in regard to availability and access to food sources and the genetic resources supporting their production (Khoury et al., 2014), result in the increasing reliance of some regions on social and natural resources from other regions of the world, which also increases agri-food debt. A clear example of this phenomenon is land grabbing, which is largely exerted by companies mostly from countries in groups 3 (Middle East), 2 (e.g., China) and 5 (e.g., Europe) on countries from group 1 (e.g., Africa) (Anseeuw, 2013; Batterbury & Ndi, 2018). For example, restrictions on agricultural production and changes in bioenergy demand have nurtured the dependence of the EU (group 5) on the appropriation of biological productivity outside its boundaries, with increasing reliance on Latin America as the main supplier (Kastner et al., 2014). Additional evidence in that direction is related to food loss and waste: industrialized Asia (China, India, and North Korea), Europe, North America, and Oceania have the highest per capita carbon footprint of food loss and waste, while Sub-Saharan Africa has the lowest (FAO, 2013).

Limitations

The intricacy and complexity of the currently globalized food system are impossible to fully disentangle with a purely statistical exercise, like the one presented here. A participatory, qualitative assessment with stakeholder collaboration could improve both the selection of indicators and the interpretation of results, for example, be tailored at the national or regional levels, therefore also improving the usability of the knowledge generated (Clark et al., 2016). Moreover, using the country scale as a unit of analysis implies that internal environmental, social, and nutritional inequities cannot be accounted for. For example, data on ethnic minorities, regional groups, indigenous populations, slum dwellers, and women aged 50 and over are rarely collected (Swain, 2018). A further constraint is the limited quality and/or availability of data: while data on economic indicators are widely available for most countries, data on environmental and social indicators of contested phenomena (e.g., land grabbing) are incomplete and of poor quality (Swain, 2018). However, providing quantitative agri-food system metrics at the global scale using Food Sovereignty indicators together with other socio-demographic, social wellbeing and environmental indicators allows the identification of trade-offs in environmental and social justice within the global agri-food system, which is currently largely ignored (van Vuuren et al., 2015) but needed in order to address SDGs.

4 Conclusions

In the last four decades, there has been an intense debate about the best policies needed to achieve what is currently stated in SDG2. Between the mid-1960s and the early 2000s, food availability improved globally, and global per capita exports of agricultural products almost doubled, but food self-sufficiency did not change significantly (Porkka et al., 2013). The global population increased by 142% between 1961 and 2016, while calorie production increased by 217% by 2013 (McKeon, n.d.). While the need to increase food production has been repeated like a mantra in many instances (FAO, 2009; West et al., 2014a), old policies focused on productivity, favoring agricultural industrialization, trade liberalization, privatization, and deregulation, have failed to end hunger (Burdock & Ampt, 2017). As this study corroborates, under-nutrition is not only a matter of food availability and access (Porkka et al., 2013; Schipanski et al., 2016). Instead, the eradication of hunger would be facilitated by a redistribution of current consumption levels (Pittelkow et al., 2015). Furthermore, the challenges and responsibility for achieving SDG2, as well as other SDGs, still within planetary boundaries, are not evenly distributed across the globe (Easterly, 2015; Swain, 2018; West et al., 2014a). On a global scale, agri-food debt shows that wealthy countries are exporting environmental degradation to import cheap food that they largely waste and overeat: European and North American countries (groups 4 and 5) currently hold an important stake.

There is no fundamental trade-off between eradicating hunger, achieving environmental sustainability (van Vuuren et al., 2015), and social equity. However, for the achievement of SDG2 through transformational, socially fair, environmentally sustainable, and resilient food systems, our results point to the following key wedges: biodiversity conservation through environmentally friendly agri-food practices (M. Altieri, 2009), the reduction of agri-food waste (Schipanski et al., 2016), the regionalization of food distribution (Schipanski et al., 2016) and the adoption of healthy and sustainable diets (Vermeulen et al., 2012). We need to make these steps fast enough to advance SDG2 while preserving environmental sustainability and social wellbeing.

5 Materials and methods

Data collection

We based the selection of our data collection on previous work by Ruiz-Almeida and Rivera-Ferre (2019). They compiled 97 indicators for 223 regions (countries or officially recognized territories) to analyze food sovereignty at a country level. The data collected ranged between 1961 and 2012, with some indicators presenting complete time series but others presenting few sporadic data within this timeframe.

Indicator adjustments

Nine indicators were selected to describe the pillar of “access to resources”, 16 for “productive models”, 8 for “commercialization”, 5 for “food security and consumption”, 3 for “agrarian policies and civil society organization”, and 2 for “gender”. Some indicators were originally published as indexes or proportions while others needed to be transformed in relative terms with respect to country area or population size in order to adjust magnitudes and allow comparison between countries. Table S1 shows all the adjusted indicators of FSv and Table S2 the indicators that did not need any adjustment, in both cases with a brief description of the indicator and data sources.

Indicator	Description	Sources
Access to Resources		
Land, Forest and Marine Resources		
agric_area	Agricultural area (hectares / capita)	FAOSTAT/FAOSTAT
biofuels	Total of crops for Biodiesel and Bioethanol (Rapeseed, Soybeans and Sugar Cane (% of the total arable land)	FAOSTAT/FAOSTAT
Animals		
mammals	Domestic mammals per rural inhabitant (except pack animals) (number of animals / capita of rural population)	FAOSTAT/FAOSTAT
poultry	Poultry animals per rural inhabitant (number of animals / capita of rural population)	FAOSTAT/FAOSTAT
pack_anim	Pack animals per square km of agricultural area (number of animals / km of agricultural area)	FAOSTAT/FAOSTAT
Productive Models		
Population & Employment		
rural_pop	Rural population (% of total population)	FAOSTAT/FAOSTAT
agric_pop	Agricultural population (% of total population)	FAOSTAT/FAOSTAT
tae_agric	Total economically active population in agriculture (% of total employment)	FAOSTAT/FAOSTAT
Land Use		
perm_crop	Permanent crops (% of agricultural area)	FAOSTAT/FAOSTAT
meadows	Meadows and permanent pasture (% of agricultural area)	FAOSTAT/FAOSTAT
forest_area	Forest area (% of country area)	FAOSTAT/FAOSTAT
Production		
cult_area	Cultivated area (hectares / capita of agricultural population)	FAOSTAT/FAOSTAT
cereals_prod	Production of cereals per person (kg / capita)	FAOSTAT/FAOSTAT
meat_prod	Production of meat per person (kg / person)	FAOSTAT/FAOSTAT
fruit_prod	Production of fruit per person - excluding melons (kg / capita)	FAOSTAT/FAOSTAT
fish_prod	Fishery production per person (kg / capita)	FISHSTAT/FAOSTAT
Agricultural Inputs		
pesticides	Intensity of total pesticides use (tons / hectare of cultivated area)	FAOSTAT/FAOSTAT
Commercialization		
International Trade		
forest_imp	Imports of forest products (% of imports, in dollars)	FAOSTAT/FORESTAT
forest_exp	Exports of forest products (% of exports, in dollars)	FAOSTAT/FORESTAT
fishery_imp	Fishery imports (% of imports, in dollars)	FISHSTAT/FAOSTAT
fishery_exp	Fishery exports (% of exports, in dollars)	FISHSTAT/FAOSTAT

Indicator	Description	Sources
Gender		
Population & Employment		
active_agric_fem	Female economically active population in agriculture (% of total female employment)	FAOSTAT/FAOSTAT

Table S11. Adjusted indicators of food sovereignty.

Indicator	Description	Source
Access to Resources		
Basic Infrastructure and Services		
electricity	Access to electricity by rural population (% rural pop.)	WB
enrollment	Total net enrollment ratio in primary education (% of children)	MDG
sanitation	Use of improved sanitation facilities by rural population (% rural pop.)	UN Data
drink_water	Use of improved drinking water sources by rural population (% rural pop.)	UN Data
Water		
renew_water	Total internal renewable water (cubic meters / capita / year)	AQUASTAT
Productive Models		
Production		
forest_rate	Forest harvest rate (% of forest volume)	GEODATA
Agricultural Inputs		
fertilizers	Intensity of the total fertilizer use (tons/hectare of cultivated area)	WDI
pesticides	Intensity of the total pesticide use (tons/hectare of cultivated area)	WDI
primary_forest	Primary forest extent (% of forest area)	GEODATA
Economic Characteristics		
value_added	Value added in agriculture (% of GDP)	WDI
organic_agric	Organic agricultural area (% of total agricultural area)	IFOAM y FIBL
Commercialization		
International Trade		
agric_exp	Agricultural raw materials exports (% merchandise exports in $)	WDI
agric_imp	Agricultural raw materials imports (% merchandise imports in $)	WDI
food_exp	Food exports (% of merchandise exports in $)	WDI
food_imp	Food imports (% of merchandise imports in $)	WDI
Food Security and Food Consumption		
Food Scarcity		
food_deficit	Depth of the food deficit (kilocalories/capita * day)	WDI
Food & Nutrients Consumption		
energy_adequacy	Average dietary energy supply adequacy (3-year average, %)	FAOSTAT
protein_supply	Average protein supply (3-year average, g / capita*day)	FAOSTAT
External Food Dependency		
dependency	Cereal import dependency ratio (3-year average, %)	FAOSTAT
The vulnerability of Food Consumption		
vulnerability	Share of dietary energy supply derived from cereals, roots, and tuber (3-year average, %)	FAOSTAT

Indicator	Description	Source
Agrarian Policies and Civil Society Organizations		
Official Development Assistance Dedicated to Agriculture		
agric_oda	ODA received/contributed to agriculture, forestry, fishing ($ million)	OECD
Tariffs Related to International Trade of Agricultural Products		
final_bound	Tariff, Final bound simple average for agricultural products (%)	WTO
Local and International Governance		
globalization	KOF Index of Globalization	(12)
Gender		
Food Scarcity		
pregnant_anemia	Prevalence of anemia among pregnant women (%)	FAOSTAT

Table S12. Non-adjusted indicators of food sovereignty

World food sovereignty database

The database comprises 97 indicators as a reference framework to measure food sovereignty's different aspects (https://foodsovereigntyindicators.uvic.cat). However, some of the indicators suggested by the authors might not be relevant depending on the context and scale in which detailed analyses are performed, or they present repeated information. For the objectives of the present research, we performed a selection of indicators following four main steps (Fig. S12):

a) We retrieved all the historical data available from all indicators;

b) We selected the indicators for which the last data available referred to the timeframe between 2008 and 2012. For 223 countries or territories, 92 indicators fulfilled these criteria;

c) We debug the database to 1) minimize the repetition of information in different indicators, 2) reduce extrapolation of data as much as possible, and 3) avoid outliers due to country or population size;

d) And finally, we added extra data that characterized the country's bioregional location, the social well-being, and environmental sustainability of each country.

The Debug Process

The debug process reduced the initial database from 223 countries and 92 indicators to 150 countries and 43 indicators in five steps. In the final database, there were 200 missing values (3.1% of the full database) that were estimated through the Non-linear Iterative Partial Least Squares (NIPALS) algorithm with XLSTAT.

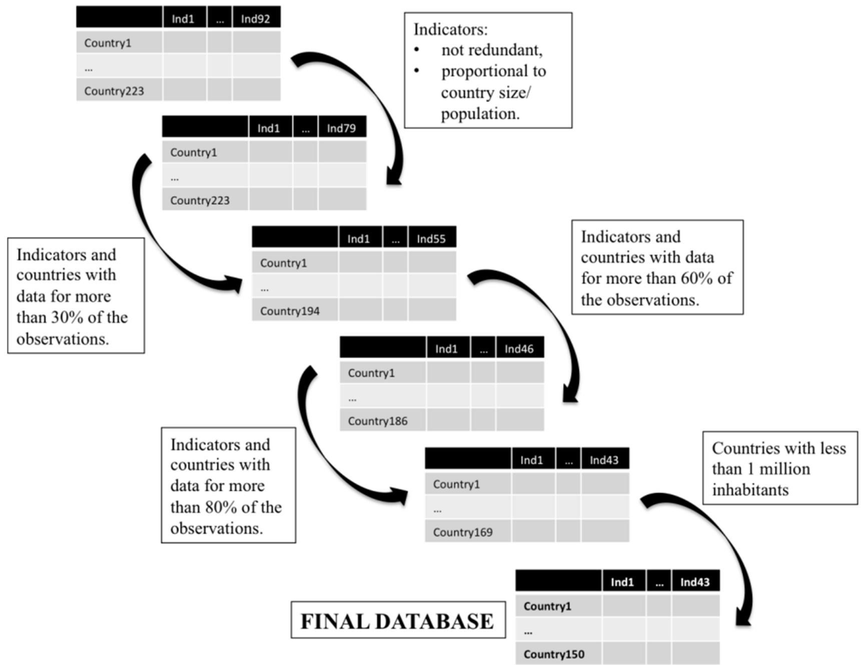

Fig. S12. The Debug Process.

The text in the squares indicates the data removed in each step.

Selection of environmental sustainability and social wellbeing indicators

In order to relate the state of FSv of the groups of countries with their state of social wellbeing and environmental sustainability, a further selection of indicators was made. We scanned more than 200 indicators of social wellbeing and environmental sustainability and selected 17 for environmental sustainability (Table S3) and 5 for social wellbeing (Table S4), based on the following criteria:

a) Capacity to express the required information;
b) Availability of the information for a sufficient number of countries;
c) Availability of the information for the selected timeframe (2008-2012);
d) Veracity of the data according to internationally legitimized sources.

Indicator	Description	Year	Source
Cropland Footprint	Consists of areas used to produce food and fiber for human consumption, feed for livestock, oil crops, and rubber. Includes crop products allocated to livestock and aquaculture feed mixes, and those used for fibers and materials.	2011	Global Foot-print Net-work
Grazing Footprint	Is calculated by comparing the amount of livestock feed available in a country with the amount of feed required for all livestock in that year, with the remainder of feed demand assumed to come from grazing land.		
Forest Product Footprint	Is calculated based on the amount of lumber, pulp, timber products, and fuel wood consumed by a population on a yearly basis.		
Carbon Footprint	Represents the carbon dioxide emissions from burning fossil fuels in addition to the embodied carbon in imported goods. The carbon Footprint component is represented by the area of forest land required to sequester these carbon emissions. Currently, the carbon Footprint is the largest portion of humanity's Footprint.		
Fish Footprint	Is calculated based on estimates of the maximum sustainable catch for a variety of fish species. These sustainable catch estimates are converted into an equivalent mass of primary production based on the various species' trophic levels. This estimate of maximum harvestable primary production is then divided amongst the continental shelf areas of the world. Fish caught and used in aquaculture feed mixes are included.		
Built up land Footprint	Is calculated based on the area of land covered by human infrastructure: transportation, housing, industrial structures, and reservoirs for hydro-power. Built-up land may occupy what would previously have been cropland.		
Total Ecological Footprint	Is the area of land and water it takes for a human population to generate the renewable resources it consumes and to absorb the corresponding waste it generates, using prevailing technology. In other words, it measures the "quantity of nature" that we use and compares it with how much "nature" we have.		
Cropland Biocapacity	Is the combined productivity of all land devoted to growing crops.		
Grazing land Biocapacity	Is the combined productivity of all grasslands used to provide feed for animals, including cultivated pastures and wild grasslands and prairies.		
Forest land Biocapacity	Is the combined productivity farmed or natural forests that can be used either to generate forest products to harvest or to sequester carbon.		
Fishing ground Biocapacity	Is the combined productivity of the total area of water, both marine and inland, that act as fishing grounds.		
Built up land Biocapacity	Built-up land always has a biocapacity equal to its Footprint since both quantities capture the amount of bioproductivity lost to encroachment by physical infrastructure.		
Total Biocapacity	Biocapacity refers to the amount of biologically productive land and water areas available within the boundaries of a given country.		
Biocapacity (Deficit) or Reserve	Is the difference between the biocapacity and Ecological Footprint of a region or country.		
Terrestrial Protected Areas	Percentage of terrestrial biome area that is protected, weighted by the global contribution of each terrestrial biome.		
Agricultural total CO2 emissions per capita	Kilograms of CO_2eq emissions from agriculture divided by country's population. It includes non-CO_2 gases, namely methane (CH_4) and nitrous oxide (N_2O), produced by crop and livestock production and management activities."	2012	FAO-STAT
Agricultural water withdrawal per capita	Number of m^3 of water per capita per year withdrawn y agriculture, including irrigation, livestock watering and cleaning, and aquaculture.	2012	AQUA-STAT

Table S13. Indicators of environmental sustainability, the year of the data used, and the source of the data.

Indicator	Description	Year	Source
Life Expectancy	Number of years a newborn infant could expect to live if prevailing patterns of age-specific mortality rates at the time of birth stay the same throughout the infant's life.	2011	UNDP Human Development Report
Life Satisfaction	Arithmetic mean of individual responses to the Ladder of Life question in the Gallup World Poll.	2012	Gallup World Poll
Global Peace Index	Ranks countries according to their level of peacefulness by 23 qualitative and quantitative indicators from highly respected sources.	2012	Institute for Economics and Peace
Freedom in the World	Assess the condition of political rights and civil liberties around the world. A country is awarded 0 to 4 points for each of 10 political rights indicators and 15 civil liberties indicators, which take the form of questions; a score of 0 represents the smallest degree of freedom and 4 the greatest degree of freedom.	2012	Freedom House
Gini Land Index	Gini coefficient for land distribution measures inequality or concentration in a distribution of land. It is defined as a ratio with values between 0 and 1, where 0 corresponds to perfect equality and 1 to perfect inequality.	52 figures between 1994 and 2002	FAO Statistical Yearbook 2010

Table S14. Indicators of social wellbeing, the year of the data that was used and the source of the data.

Selection of other relevant indicators

For the description of the demographic and economic contexts of the countries seven indicators were selected (Table S5).

Indicator	Description	Year	Source
Income Group	2012 World Bank's income classification: low-income economies (LI), Lower-middle-income economies (LM), Upper-middle-income economies (UM) and high-income economies (HI)	2012	World Bank (WB)
GDP/capita	Gross domestic product (GDP) per capita (current USD)	2012	WDI (WB)
Population density	Population density (habitants per hectare)	2012	WDI (WB)
Population	Million inhabitants per country	2012	WDI (WB)
Land Area	Total country land area (1000 hectares)	2012	WDI (WB)
Land grabbed	Percentage of the total country area that is being grabbed by foreign companies	2012	GRAIN
Land grabber	Percentage of its total area that the country is grabbing elsewhere	2012	

Table S5. Demographic and economic indicators.

For the bioregional characterization of the groups, we used a synthesis of the classification of the world ecoregions, i.e. the 26 categories of which 14 terrestrial, 7 inland water and 5 marine (Table S6).

Indicator	Description
Boreal Forests / Taiga	Dummy variable that shows whether the country has or not boreal forests or Taiga ecoregions that are ecoregions with low annual temperatures, precipitation ranges between 40-100 centimeters per year and may fall mainly as snow.
Deserts and Xeric Shrublands	Dummy variable that shows whether the country has or not deserts and xeric shrublands ecoregions, with variable rainfalls where evaporation exceeds rainfall.
Flooded Grasslands and Savannas	Dummy variable that shows whether the country has or not flooded grasslands and savanna ecoregions, which support numerous plants and animals adapted to the unique hydrologic regimes and soil conditions.
Large Lakes	Dummy variable that shows whether the country has or not large lakes.
Large River Deltas	Dummy variable that shows whether the country has or not freshwater ecoregions with large river delta ecosystems.
Large River Headwaters	Dummy variable that shows whether the country has or not fresh water ecoregions with larger river headwater ecosystems. Species, assemblages, and processes in headwater areas are distinct from those of their larger mainstreams.
Large Rivers	Dummy variable that shows whether the country has or not freshwater ecoregions with large river ecosystems.
Mangroves	Dummy variable that shows whether the country has or not mangrove ecoregions. Mangroves occur in the waterlogged, salty soils of sheltered tropical and subtropical shores.
Mediterranean Forests, Woodlands and Scrub	Dummy variable shows whether the country has or not Mediterranean forests, woodlands, and scrub ecoregions characterized by hot and dry summers, while winters tend to be cool and moist.
Montane Grasslands and Scrublands	Dummy variable that shows whether the country has or not montane grasslands and scrublands ecoregions, defined by high elevation (montane and alpine) grasslands and scrublands.
Polar Seas	Dummy variable that shows whether the country has or not polar seas; marine habitats defined by low temperatures, low salinity, high plankton levels and correspondingly green color generally characterize Polar marine waters.
Small Lakes	Dummy variable that shows whether the country has or not freshwater ecoregions with small lake ecosystems that host extraordinary expressions of freshwater biodiversity.
Small Rivers	Dummy variable that shows whether the country has or not freshwater ecoregions with small river ecosystems.
Temperate Broadleaf and Mixed Forests	Dummy variable that shows whether the country has or not temperate broadleaf and mixed forests ecoregions, forests with a wide range of variability in temperature and precipitation.
Temperate Coniferous Forests	Dummy variable that shows whether the country has or not temperate coniferous forests, which predominantly are found in areas with warm summer and cool winters, and vary enormously in their kinds of plant life.
Temperate Grasslands, Savannas and Scrublands	Dummy variable that shows whether the country has or not temperate grasslands, savannas and scrublands. Generally, these regions are devoid of trees, except for riparian or gallery forest associated with streams and rivers.

Table S6. Ecoregions.

Indicator	Description
Temperate Shelfs and Seas	Dummy variable that shows whether the country has or not temperate shelfs and seas. The relative shallowness of these regions (the continental shelf extends to an average maximum depth of 150 meters) leads to warmer temperatures and seasonal stratification of the water column based on temperature.
Temperate Upwelling	Dummy variable that shows whether the country has or not temperate upwelling regions. These regions are continental margins characterized by the consistent welling up of nutrient rich bottom waters to the surface.
Tropical and Subtropical Coniferous Forests	Dummy variable that shows whether the country has or not tropical and subtropical coniferous forests, regions with diverse species of conifers, low level of precipitation and moderated variability in temperatures.
Tropical and Subtropical Dry Broadleaf Forests	Dummy variable that shows whether the country has or not tropical and subtropical dry broadleaf forests ecoregions. These habitats are warm year-round, and may receive several hundred centimeters of rain per year, they deal with long dry season which last several months and day with geographic location.
Tropical and Subtropical Grasslands, Savannas and Scrublands	Dummy variable that shows whether the country has or not tropical and subtropical grasslands, savannas and scrublands. Large expanses of land in the tropics that do no receive enough rainfall to support extensive tree cover.
Tropical and Subtropical Moist Broadleaf Forests	Dummy variable that shows whether the country has or not tropical and subtropical moist broadleaf forests ecoregions, generally found in large, discontinuous patches centered on the equatorial belt and between the Tropics of Cancer and Capricorn. They are characterized by low variability in annual temperature and high levels of rainfall.
Tropical Coral	Dummy variable that shows whether the country has or not the greatest known species diversity of any marine ecosystem, coral reefs.
Tropical Upwelling	Dummy variable that shows whether the country has or not tropical welling habitats, characterized by high productivity resulting from the upwelling of nutrient rich bottom waters.
Tundra	Dummy variable that shows whether the country has or not Tundra, a treeless polar desert found in the high latitudes in the polar regions
Xeric Basins	Dummy variable that shows whether the country has or not freshwater ecoregions with xeric basin ecosystems (little permanent surface water and a relative abundance of springs).

Table S6. Ecoregions (cont.)

Data analyses

Preparation of variables

Tests for normality of the distributions of all 43 indicators of FSv were performed. Only one indicator proved to follow a normal distribution and was standardized (n-1). The indicators that did not follow a normal distribution nor show negative values, were transformed through Ln(x), or Ln(x+1) when the indicator (x) showed value equal to 0. The indicators that did not follow a normal distribution and showed negative values were first rescaled (0-100) and then transformed through Ln(x+1).

Statistical analyses

For the identification of groups of countries we carried out a Principal Component Analysis (PCA, covariance (n-1)) based on the matrix of countries (observations) and indicators (variables). We followed the Kaiser criterion (eigenvalue >1) to determine the significant number of components. In order to identify possible groups of countries with a similar values of FSv indicators, we carried out a Hierarchical Cluster Analysis (HCA) based on the Euclidean distance (percentage of distance similarity at a 95% level of confidence) and the Ward's agglomerative method (16) using the standardized coordinates of the most significant factors of the PCA. Finally, in order to characterize each group resulting from the HCA in terms of ecoregions, socio-economic characteristics, FSv, social wellbeing and environmental sustainability indicators we performed Kruskal-Wallis and Chi^2 tests.

Results

Nine factors from the PCA showed an eigenvalue>1 and absorbed a total of 72% of variance. The factors loadings of the countries in these factors were used to perform the HCA (Table S7).

Categories	Indicators	F1	F2	F3	F4	F5	F6	F7	F8	F9
Access to resources	Ln(electricity)	**-0,794**	-0,279	0,072	0,115	0,103	-0,121	0,003	-0,23	0,039
	Ln(sanitation)	**-0,782**	-0,308	0,033	0,093	0,18	-0,202	-0,009	-0,088	0,022
	Ln(drink_water)	**-0,814**	-0,302	0,041	-0,04	0,104	-0,038	-0,084	-0,061	-0,125
	Ln(agric_area)	0,193	**0,771**	0,078	0,157	0,217	-0,102	0,131	-0,258	-0,08
	Ln(biofuels+1)	-0,265	-0,035	0,376	0,27	0,289	-0,023	-0,285	0,16	-0,192
	Ln(mammals)	-0,37	**0,675**	-0,102	0,205	0,222	0,315	-0,007	0,013	0,117
	Ln(poultry)	**-0,679**	0,055	0,181	0,325	-0,133	0,273	-0,197	-0,066	-0,128
	Ln(pack_anim+1)	-0,02	-0,314	-0,105	0,142	0,337	0,166	0,178	**0,414**	0,063
	Ln(renew_water+1)	-0,007	0,21	**0,749**	-0,087	-0,048	-0,057	0,318	-0,057	0,089
Productive Models	Ln(cult_area+1)	**-0,728**	0,434	0,003	-0,318	0,094	-0,162	0,091	0,017	-0,123
	Ln(rural_pop)	**0,718**	-0,269	0,041	-0,23	0,155	-0,288	0,105	-0,062	-0,112
	Ln(agric_pop)	**0,912**	-0,032	0,156	-0,029	0,147	0,059	-0,089	-0,132	-0,073
	Ln(tae_agric)	**0,913**	-0,038	0,158	-0,04	0,142	0,069	-0,099	-0,145	-0,074
	Ln(perm_crop+1)	0,018	**-0,68**	0,199	0,006	-0,098	0,198	-0,05	0,031	-0,069
	Ln(meadows)	0,172	0,472	-0,153	**0,52**	0,135	0,004	0,247	-0,158	0,115
	Ln(forest_area+1)	-0,059	-0,044	**0,708**	-0,139	-0,379	-0,114	0,181	0,123	0,042
	Ln(cereals_prod+1)	-0,441	0,359	0,221	**-0,487**	0,284	-0,236	-0,147	-0,175	-0,273
	Ln(meat_prod+1)	**-0,686**	0,372	0,192	-0,085	0,256	0,242	-0,057	0,134	0,041
	Ln(fruit_prod+1)	-0,11	-0,214	0,432	0,289	0,175	0,301	0,155	-0,089	-0,021
	Ln(fish_prod)	-0,163	-0,031	**0,445**	-0,148	-0,308	0,358	-0,032	-0,054	-0,251
	Ln(fertilizers)	**-0,687**	-0,412	0,08	0,144	0,015	0,036	-0,166	-0,02	0,166
	Ln(pesticides+1)	-0,32	-0,197	0,29	0,156	0,009	-0,011	0,079	-0,173	0,045
	Ln(primary_forest+1)	0,036	-0,015	**0,608**	0,105	0,045	-0,082	-0,032	-0,252	0,343
	Ln(value_added)	**0,849**	-0,07	0,107	-0,117	0,26	0,058	-0,043	-0,114	-0,092
	Ln(organic_agric+1)	**-0,498**	0,046	-0,052	-0,324	0,01	-0,123	0,234	0,316	0,135
Commercialization	Ln(agric_exp+1)	0,41	0,172	0,261	**-0,417**	0,123	0,258	0,073	0,106	0,071
	Ln(agric_imp+1)	-0,15	-0,371	-0,166	**-0,433**	0,173	0,163	-0,151	-0,231	0,122
	Ln(food_exp+1)	0,286	-0,106	0,287	-0,116	**0,573**	0,229	0,038	0,253	-0,143
	Ln(food_imp)	**0,436**	-0,191	-0,269	0,127	0,089	0,224	0,364	0,087	-0,13
	Ln(fishery_imp+1)	0,004	0,008	0,086	0,015	-0,003	-0,022	0,028	-0,008	-0,04
	Ln(fishery_exp+1)	0,042	-0,045	0,056	0,064	0,025	0,053	0,038	0,031	0,008
	Ln(forest_imp+1)	-0,339	-0,449	-0,181	-0,093	**0,464**	-0,079	0,139	-0,233	0,188
	Ln(forest_exp+1)	-0,018	-0,031	0,151	-0,105	0,007	-0,021	0,01	0,049	-0,072
Food Security and Consumption	Ln(food_deficit)	**0,853**	-0,09	0,206	0,199	0,1	-0,156	-0,08	0,104	0,146
	Ln(protein_supply)	**-0,826**	0,083	-0,186	-0,113	0,032	0,104	0,003	-0,092	-0,101
	energy_adequacy	**-0,703**	0,032	-0,215	-0,152	-0,07	0,335	-0,039	-0,19	-0,214
	Ln(dependency(0-100)+1)	0,063	-0,235	-0,106	-0,168	-0,071	-0,033	**0,563**	-0,138	-0,247
	Ln(vulnerability)	**0,853**	-0,097	-0,11	-0,008	-0,018	-0,001	-0,12	-0,234	-0,001
	Ln(agric_oda)	0,016	0,207	0,005	-0,429	-0,015	0,073	-0,215	0,114	**0,455**
	Ln(final_bound)	-0,052	-0,036	-0,105	-0,234	-0,071	**0,449**	0,241	-0,272	0,337

Categories	Indicators	F1	F2	F3	F4	F5	F6	F7	F8	F9
Agrarian Policies and Civil Society Organization	Ln(globalization)	**-0,817**	-0,008	0,015	-0,12	-0,048	-0,012	0,066	0,053	0,003
Gender	Ln(active_agric_fem+1)	**0,879**	0,045	-0,089	-0,211	0,009	0,093	-0,149	-0,019	0,006
	Ln(pregnant_anemia)	**0,734**	0,121	-0,073	-0,046	-0,212	0,242	-0,087	-0,028	-0,111
PCA values	*Eigenvalue*	*12,8*	*3,5*	*2,82*	*2,09*	*1,63*	*1,43*	*1,21*	*1,1*	*1,05*
	Variability (%)	*33,35*	*9,13*	*7,34*	*5,44*	*4,24*	*3,73*	*3,16*	*2,86*	*2,72*
	Accumulated variability (%)	*33,35*	*42,48*	*49,82*	*55,25*	*59,49*	*63,22*	*66,39*	*69,25*	*71,97*

Table S7. Factor loadings derived from the principal component analysis (PCA) to characterize countries concerning their performance in the five categories of food sovereignty. Bold numbers correspond to the largest square cosine in each factor.

The HCA resulted in five groups of countries formed by 45, 49, 18, 8 and 30 countries, respectively (Fig.1, Fig. S4 and Table S8).

HCA groups	Group 1	Group 2	Group 3	Group 4	Group 5
Number of objects	45	49	18	8	30
Intra-group variance	11,686	17,595	13,142	18,668	8,314
Countries	Afghanistan	Albania	Algeria	Argentina	Austria
	Angola	Armenia	Belgium	Australia	Belarus
	Bangladesh	Azerbaijan	Cuba	Brazil	Bosnia and Herzegovina
	Benin	Barbados	Greece	Canada	Bulgaria
	Botswana	Belize	Iraq	Denmark	Croatia
	Burkina Faso	Bolivia	Israel	New Zealand	Czech Rep.
	Burundi	Cabo Verde	Jordan	United States	Estonia
	Cambodia	Chile	Kuwait	Uruguay	Finland
	Cameroon	China	Lebanon		France
	Central African Rep.	Colombia	Libya		Germany
	Chad	Costa Rica	Mexico		Hungary
	Congo	Cyprus	Oman		Ireland
	Cote d'Ivoire	Dominican Rep.	Panama		Italy
	Ethiopia	Ecuador	Portugal		Kazakhstan
	Gambia	Egypt	Saudi Arabia		Latvia
	Ghana	El Salvador	South Africa		Lithuania
	Guinea	Fiji	United Arab Emirates		Luxembourg
	Guinea-Bissau	Gabon	Venezuela		Netherlands
	Haiti	Georgia			Norway
	Kenya	Guatemala			Poland
	Lao People's Democratic Rep.	Guyana			Romania
	Lesotho	Honduras			Russian Federation
	Madagascar	India			Serbia
	Malawi	Indonesia			Slovakia
	Mali	Iran			Slovenia
	Mauritania	Jamaica			Spain
	Mongolia	Japan			Sweden
	Mozambique	Kyrgyzstan			Switzerland
	Myanmar	Macedonia			Ukraine
	Namibia	Malaysia			United Kingdom
	Nepal	Mauritius			
	Niger	Morocco			
	Nigeria	Nicaragua			
	Pakistan	Paraguay			
	Rwanda	Peru			
	Senegal	Philippines			
	Sierra Leone	Rep. of Korea			
	Sudan	Rep. of Moldova			
	Timor-Leste	Sri Lanka			
	Togo	Suriname			
	Uganda	Swaziland			
	United Rep. of Tanzania	Syrian Arab Rep.			
	Yemen	Tajikistan			
	Zambia	Thailand			
	Zimbabwe	Trinidad and Tobago			

HCA groups	Group 1	Group 2	Group 3	Group 4	Group 5
		Tunisia Turkey Uzbekistan Vietnam			

Table S8. The number of objects (countries), intra-group variance, and list of countries in each of the five groups resulting from the hierarchical cluster analysis (HCA).

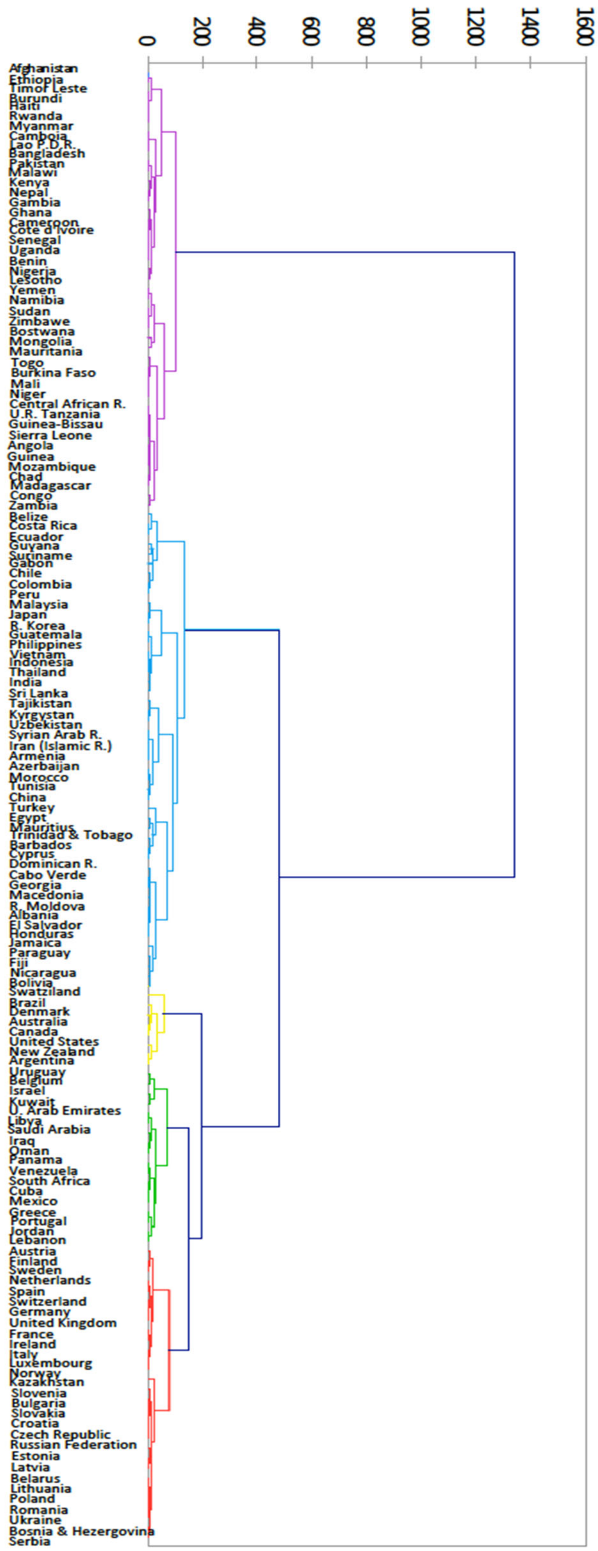

Fig. S4. Cluster resulting from the HCA. The axis corresponds to the values of dissimilarity.

The detailed characterization of the five groups is hereby structured in four groups of dimensions: bioregional context (Table S9), socio-economic context and land grabbing (Table S10), FSv (Table S11), environmental sustainability and social wellbeing (Table S12).

	Indicator	Group 1	Group 2	Group 3	Group 4	Group 5	*p-value*	Chi2/K (obs)	Chi2 (cri)
Continent							< 0,0001	181,09	26,30
	Africa	>*	<*	<	<*	<*			
	Americas	<*	>*	>	>*	<*			
	Asia	<	>*	>	<*	<*			
	Europe	<*	<*	<	<	>*			
	Oceania	<*	<*	<*	>*	<*			
Subregion							< 0,0001	256,84	83,68
	Australia and New Zealand	<*	<*	<*	>*	<*			
	Caribbean	<	>	>	<*	<*			
	Central America	<*	>	>	<*	<*			
	Central Asia	<*	>	<*	<*	>			
	Eastern Africa	>*	<*	<*	<*	<*			
	Eastern Asia	<	>	<*	<*	<*			
	Eastern Europe	<*	<*	<*	<	>*			
	Middle Africa	>*	<	<*	<*	<*			
	Northern Africa	<	>	>	<*	<*			
	Northern America	<*	<*	<*	>*	<*			
	South America	<*	>	<	>*	<*			
	South-Eastern Asia	<	>	>*	<*	<*			
	Southern Africa	>	<	>	<*	<*			
	Southern Asia	>	>	<*	<*	<*			
	Southern Europe	<*	<	>	<*	>*			
	Western Africa	>*	<*	<*	<*	<*			
	Western Europe	<*	<*	>	<*	>*			
Ecoregions	Boreal Forests / Taiga						0,060		
	Deserts and Xeric Shrublands						0,156		
	Flooded Grasslands and Savannas	>*	<*	<*	>	<*	< 0,0001	24,39	9,49
	Large Lakes						0,058		
	Large River Deltas						0,247		
	Large River Headwaters	>	>	<*	>	<*	< 0,05		
	Large Rivers						0,288		
	Mangroves						0,083		
	Mediterranean Forests, Woodlands and Scrub	<*	<	>*	>	>	< 0,0001	25,58	9,49

	Montane Grasslands and Shrublands	>*	>	<	<	<*	< 0,05	12,00	9,49
	Polar Seas	<*	<*	<*	>*	>	< 0,01	18,34	9,49
	Small Lakes						0,681		
	Small Rivers						0,311		
	Temperate Broadleaf and Mixed Forests	>	<*	<*	>*	<	< 0,05	13,04	9,49
	Temperate Coniferous Forests	<*	>	<	>	>*	< 0,0001	27,19	9,49
	Temperate Grasslands, Savannas and Shrublands	<	<	<*	>*	<	< 0,01	18,21	9,49
	Temperate Shelfs and Seas	<*	<	<	>*	>*	< 0,0001	60,10	9,49
	Temperate Upwelling						0,153		
	Tropical and Subtropical Coniferous Forests						0,233		
	Tropical and Subtropical Dry Broadleaf Forests	<	>	<	>	<*	< 0,05	10,03	9,49
	Tropical and Subtropical Grasslands, Savannas and Shrublands	>*	<*	<*	>	<*	< 0,0001	27,42	9,49
	Tropical and Subtropical Moist Broadleaf Forests	>*	>	<*	>	<*	< 0,0001	26,15	9,49
	Tropical Coral	<	>	>	>	<*	< 0,05	11,07	9,49
	Tropical Upwelling						0,155		
	Tundra	<*	<*	<*	>	>*	< 0,001	19,99	9,49
	Xeric Basins	<*	>	>	>	<*	< 0,05	12,66	9,49
Country size	Land Area (1000km2)	53,07	55,86	65,15	468,73	81,13	< 0,05	12,84	9,49

Table S9. Results of the Chi-square tests and Kruskal-Wallis comparison between the five groups resulting from the HCA in terms of continents, subregions, ecoregions, and country size. * indicate comparisons statistically significant at alpha=0,05. Cells in grey indicate the predominance of a continent, region, or subregion within a group (i.e. “>*”).

Indicator		Group 1	Group 2	Group 3	Group 4	Group 5	*p-value*	Chi2/K (obs)	Chi2 (cri)	Pair comparisons (Dunn)
Socio-economic	GDP/capita	6,83	8,44	9,51	10,25	9,93	< 0,0001	104,74	9,49	1A; 2B; 3BC; 4C; 5C
	Population (million hab)	28,15	79,57	21,90	78,68	23,48	0,548			1A; 2A; 3A; 4A; 5A
	Pop/density (hab/km2)	114,88	145,86	122,77	31,16	108,74	< 0,05	11,80	9,49	1AB; 2B; 3AB; 4A; 5AB
	Income group						< 0,0001	161,15	26,30	
	HI	<*	<*	>	>*	>*				
	LI	>*	<*	<*	<*	<*				
	LM	<*	>*	<	<*	<*				
	UM	<*	<	>	>	>				
	ODA - Agriculture, forestry and fishing % of GDP	0,32	0,04	0,01	0,01	0,02	< 0,0001	51,64	9,49	1B; 2A; 3A; 4A; 5A
	ODA - Food Aid % of GDP	0,22	0,01	0,01	0,00	0,00	< 0,0001	47,85	9,49	1B; 2A; 3A; 4A; 5A
Land Grabbing	Land grabbed (% country area)	1,997	0,749	0,636	0,595	0,368	0,160	11,61	6,58	1A; 2A; 3A; 4A; 5A
	Land grabber (% country area)	0,035	3,395	10,643	1,623	2,351	< 0,05	10,17	14,55	1A; 2AB; 3B; 4AB; 5AB

Table S10. Results of the Chi-square tests and Kruskal-Wallis comparison of socioeconomic conditions and land grabbing between the five groups resulting from the HCA. * indicate comparisons statistically significant at alpha=0,05.

Indicator		Group 1	Group 2	Group 3	Group 4	Group 5	*p-value*	Chi2/K (obs)	Chi2 (cri)	Pair comparisons (Dunn)
Acces to resources	electricity	20,23	87,60	94,64	95,95	100,0	< 0,0001	108,0	9,49	1A; 2B; 3BC; 4BC; 5C
	sanitation	24,96	76,22	86,63	89,33	93,08	< 0,0001	94,90	9,49	1A; 2B; 3BC; 4BC; 5C
	drink_water	60,63	86,91	90,73	95,59	98,18	< 0,0001	90,17	9,49	1A; 2B; 3BC; 4BC; 5C
	agric_area	2,74	0,68	0,90	4,19	0,93	< 0,001	21,22	9,49	1AB; 2A; 3A, 4B; 5A
	biofuels	0,01	0,12	0,04	0,24	0,06	< 0,0001	28,72	9,49	1A; 2B; 3AB; 4C; 5BC
	mammals	2,46	2,07	5,57	29,23	2,50	< 0,0001	31,94	9,49	1A; 2A; 3B; 4B; 5AB
	poultry	2,71	14,06	70,28	36,95	9,68	< 0,0001	75,58	9,49	1A; 2B; 3B; 4B; 5B
	pack_anim	4,94	6,54	4,64	1,71	2,26	0,143			
	renew_water	7.072	22.375	4.923	34.225	8.617	< 0,001	20,00	9,49	1AB; 2BC; 3A; 4C; 5ABC
Productive Models	cult_area	0,42	1,27	2,14	22,40	7,01	< 0,0001	85,98	9,49	1A; 2B; 3BC; 4CD; 5D
	rural_pop	0,64	0,45	0,21	0,15	0,30	< 0,0001	84,55	9,49	1C; 2B; 3A; 4A; 5A
	agric_pop	0,61	0,23	0,08	0,08	0,06	< 0,0001	107,68	9,49	1C; 2B; 3A; 4A; 5A
	tae_agric	0,61	0,23	0,08	0,08	0,06	< 0,0001	108,03	9,49	1C; 2B; 3A; 4AB; 5A
	perm_crop	5,16	13,15	7,71	10,25	3,08	< 0,0001	27,86	9,49	1A; 2A; 3A; 4A; 5A
	meadows	59,40	47,36	66,79	63,38	37,08	< 0,01	18,81	9,49	1B; 2AB; 3B; 4B; 5A
	forest_area	0,26	0,33	0,19	0,32	0,34	< 0,05	10,43	9,49	1AB; 2AB; 3A; 4AB; 5B
	cereals_prod	0,18	0,25	0,11	0,94	0,67	< 0,0001	54,12	9,49	1A; 2AB; 3A; 4BC; 5C
	meat_prod	0,02	0,04	0,05	0,15	0,07	< 0,0001	76,79	9,49	1A; 2B; 3BC; 4C; 5C
	fruit_prod	0,07	0,16	0,12	0,24	0,07	< 0,0001	26,43	9,49	1A; 2C; 3BC; 4C; 5AB
	fish_prod	16,14	49,81	11,61	30,68	40,57	0,071			
	forest_rate	7,555	4,393	1,950	1,050	0,823	0,004	15,66	9,49	1A; 2A; 3A; 4A; 5A
	fertilizers	25,19	218,2	330,5	303,2	154,8	< 0,0001	58,80	9,49	1A; 2B; 3B; 4B; 5B
	pesticides	0,07	4,60	1,86	2,36	1,78	< 0,001	15,99	9,49	1A; 2AB; 3AB; 4AB; 5B
	primary_forest	8,04	23,23	6,30	35,38	4,37	< 0,0001	31,61	9,49	1A; 2B; 3A; 4B; 5A
	value_added	24,72	11,34	3,42	6,44	3,83	< 0,0001	73,51	9,49	1C; 2B; 3A; 4AB; AC
	organic_agric	0,00	0,01	0,02	0,02	0,06	< 0,0001	52,46	9,49	1A; 2B; 3BC; 4BC; 5C
Commercialization	agric_exp	9,38	2,22	0,66	4,23	2,24	< 0,0001	37,67	9,49	1C; 2B; 3A; 4BC; 5B
	agric_imp	1,30	1,54	0,99	1,31	1,56	< 0,05	11,01	9,49	
	food_exp	29,50	25,80	7,37	33,04	8,63	< 0,0001	32,00	9,49	1B; 2B; 3A; 4B; 5A

Indicator		Group 1	Group 2	Group 3	Group 4	Group 5	*p-value*	Chi2/K (obs)	Chi2 (cri)	Pair comparisons (Dunn)
	food_imp	16,90	13,09	11,66	8,49	9,17	< 0,0001	30,24	9,49	1B; 2AB; 3AB; 4A; 5A
	fishery_imp	0,01	0,04	0,00	2,06	0,01	0,149			
	fishery_exp	0,04	0,05	0,07	0,01	0,01	0,348			
	forest_imp	0,01	0,02	0,01	0,01	0,02	< 0,0001	43,94	9,49	1A; 2B; 3AB; 4AB; 5B
	forest_exp	0,04	0,01	0,01	0,05	0,03	< 0,0001	27,43	9,49	1A; 2A; 3A; 4B; 5B
Food Security and Consumption	food_deficit	188,47	76,37	21,19	19,38	10,90	< 0,0001	91,11	9,49	1C; 2B; 3A; 4AB; 5A
	protein_supply	61,39	77,42	89,94	97,38	99,17	< 0,0001	85,05	9,49	1A; 2B; 3BC; 4C; 5C
	energy_adequacy	109,8	119,7	131,1	133,8	130,9	< 0,0001	57,95	9,49	1A; 3B; 3C; 4C; 5C
	dependency	38,68	41,23	27,02	1,14	40,02	0,363			
	vulnerability	62,91	48,23	41,53	32,13	34,47	< 0,0001	91,74	9,49	1C; 2B; 3AB; 4A; 5A
Agrarian Policies and Civil Society Organisation	agric_oda	50,21	43,74	21,63	295,4	109,9	< 0,05	12,32	9,49	1A; 2A; 3A; 4A; 5A
	final_bound	46,53	51,04	42,98	47,09	52,26	0,976			1A; 2B; 3BC; 4BC; 5C
	globalization	43,87	58,50	64,90	67,98	78,32	< 0,0001	93,34	9,49	1A; 2B; 3BC; 4BC; 5C
Gender	active_agric_fem	0,68	0,21	0,06	0,05	0,04	< 0,0001	102,5	9,49	1C; 2B; 3AB; 4AB; 5A
	pregnant_anemia	44,55	29,92	27,99	25,99	24,99	< 0,0001	71,21	9,49	1C; 2B; 3AB; 4AB; 5A

Table S11. Results of the Chi-square tests and Kruskal-Wallis comparison of the six categories of food sovereignty between the five groups resulting from the HCA. * indicate comparisons statistically significant at alpha=0,05. The colored cells indicate the largest values for the indicator.

Indicator		Group 1	Group 2	Group 3	Group 4	Group 5	*p-value*	χ2	Pair comparisons (Dunn)
Environmental sustainability	Cropland Footprint	0,35	0,54	0,64	1,09	0,99	< 0,0001	81,70	1A; 2B; 3B; 4BC; 5C
	Grazing Footprint	0,28	0,20	0,26	0,68	0,18	< 0,001	18,52	1A; 2A; 3AB; 4B; 5A
	Forest Product Footprint	0,26	0,30	0,24	0,82	0,64	< 0,0001	41,34	1A; 2A; 3A; 4B; 5B
	Carbon Footprint	0,22	1,03	2,25	2,20	2,05	< 0,0001	92,09	1A; 2B; 3BC; 4BC; 5C
	Fish Footprint	0,05	0,12	0,10	0,17	0,12	< 0,01	16,20	1A; 2AB; 3AB; 4B; 5AB
	Built up land Footprint	0,04	0,06	0,06	0,14	0,14	< 0,0001	50,84	1A; 2A; 3A; 4B; 5B
	Total Ecological Footprint	1,21	2,26	3,54	5,10	4,15	< 0,0001	90,76	1A; 2B; 3BC; 4C; 5C
	Cropland Biocapacity	0,33	0,43	0,25	2,22	1,08	< 0,0001	65,56	1A; 2A; 3A; 4B; 5B
	Grazing land Biocapacity	0,71	0,35	0,16	2,01	0,22	< 0,01	14,66	1A; 2A; 3A; 4A; 5A
	Forest land Biocapacity	0,75	3,99	0,31	3,25	1,59	< 0,0001	33,19	1A; 2A; 3A; 4B; 5B
	Fishing ground Biocapacity	0,28	0,48	0,17	1,64	0,56	< 0,01	15,32	1A; 2A; 3A; 4B; 5A
	Built up land Biocapacity	0,04	0,06	0,06	0,14	0,14	< 0,0001	50,84	1A; 2A; 3A; 4B; 5B
	Total Biocapacity	2,09	5,32	1,01	9,26	3,92	< 0,0001	42,54	1A; 2A; 3A; 4B; 5B
	Biocapacity (Deficit or Reserve)	0,88	3,06	-2,53	4,16	-0,23	< 0,0001	44,25	1C; 2B; 3A; 4C; 5AB
	Terrestrial Protected Areas (Global Biome Weights)	58,86	55,00	55,09	57,49	71,39	0,152		
	Agricultural total CO2 emissions	1249,75	741,86	530,74	5463,64	1366,65	< 0,0001	46,23	1BC; 2AB; 3A; 4D; 5CD
	Agricultural water withdrawal	196,83	528,83	489,02	465,56	85,50	< 0,0001	49,89	1A; 2B; 3B; 4B; 5A
Social well-being	Life Expectancy	57,34	73,13	74,61	78,41	76,81	< 0,0001	90,99	1A; 2B; 3B; 4B; 5B
	Life Satisfaction	4,28	5,41	6,07	7,07	6,05	< 0,0001	68,61	1A; 2B; 3BC; 4C; 5BC
	Global Peace Index	2,27	2,10	2,14	1,61	1,67	< 0,0001	44,52	1B; 2B; 3AB; 4A, 5A
	Freedom in the World, de Freedom House	45,00	58,04	50,67	92,63	83,57	< 0,0001	51,05	1A;2A; 3A; 4B; 5B
	Gini Index	0,524	0,668	0,706	0,733	0,587	<0,05	12,935	1A; 2A; 3A; 4A; 5A

Table S12. Chi-square and Kruskal-Wallis tests of the five groups resulting from the hierarchical cluster analysis in relation to environmental sustainability and social wellbeing between. < and > signs indicate differences between pairs of levels. * indicates when these comparisons are statistically significant (p-value<0.05). For a better readability, cells in red indicate the group(s) with less environmental sustainability and social wellbeing; green cells instead indicate the groups with the highest values in environmental sustainability and social wellbeing.

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Concluding Remarks

Through the SDGs approach, the UN recognizes the importance of analyzing the various complex problems from a holistic perspective. Although there are specific indicators in each one of the objectives, many of them are intercorrelated. The agri-food system is a perfect example for that, in the way that to meet the zero hunger objective (SDG2), we do need a broader approach to food security given that the old policies focused only on productivity have failed to end hunger.

The food sovereignty framework encompasses all dimensions of sustainability while focusing its analysis on the producer rights approach. From this perspective, it offers a holistic political framework to develop sustainable agri-food systems. Nonetheless, the broader approach has not enough quantitative studies to analyze its efficiency in achieving such an objective to date.

The work presented in this thesis contributes to the complex analysis around the problem of the unsustainability of the agri-food systems. It contributes by offering quantitative and qualitative analysis of the entire system, intending to put forth tools that measure and interpret the system's functioning and degree of sustainability from a complex-systems perspective. In this line, the past chapters present three different works that support the fulfillment of the main objective of my doctoral studies: to adapt and establish critical parameters that allow characterizing the degree of sustainability of the global agri-food system following alternative framings of food, through the research and analysis of its agents, interactions, main strengths, and vulnerabilities

I highlight three main contributions of my doctoral work. The first one is the database that was a continuation of my final master's work. The base aroused great interest in the research community, which reflected the need for a multidisciplinary base of these characteristics. We have been contacted on several occasions and derived from this publication, and the data has contributed to other research works, apart from those mentioned here.

The second contribution of my thesis is the emergence of a new concept: agri-food debt. Agri-food debt is defined as *"the inter-regional social-ecological disequilibria in the natural resources consumed, the environmental impacts produced, and the social well-being attained by populations in regions that play different roles within the globalized agri-food system*." This new concept emerges from analyzing clusters of countries using the food sovereignty framework.

The third main contribution is the latest research that will be published in 2021. Using Jabareen's steps to construct the agri-food systems sustainability concept, we apply a complex networks methodology to analyze how indicators interact among them and communities. Our objective is to detect how potential decisions or policies applied to a group's elements can affect the other group members' dense connectivity among them. Within this last work scope, we will be covering the previous phases of the methodology since the final stages establish the need to clarify the interactions among the different concepts around the agri-food system's sustainability and the need to validate the conceptual framework.

As a climate change activist, I considered a lack in this work to investigate the major agri-food systems threats. However, despite not having achieved research in this area, I believed that my active participation in an international social movement aiming to fight climate change and build sustainable cities covers that lack. I have been since 2017 perusing a persona project related to the valorization of organic waste, one of the main threats to the agri-food system; with agencies the size of the United Nations, the organization of sustainable cities C40, and local governments (Mexico City and San Francisco).

Finally, besides the further work that we are in, analysis of other perspectives is needed to continue on our path to building sustainable agri-food systems. The new approach to system evaluation based on human rights and ecosystem regeneration will play an essential role in developing these new strategies. From my perspective, food sovereignty will always be based on these new analyzes as a grouping element of the dimensions of sustainability.

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